Preliminary Case Study: Design and Development of Carbondale’s Thermal Energy Network

1. Summary

The Carbondale Thermal Energy Network (TEN) case study explores the design and development of a geothermal energy system within the Three-Two Zero Energy District (32ZED) in Carbondale, Colorado, as part of the town's efforts to achieve carbon neutrality by 2050. The project involves a coalition of local partners, including CLEER, The Roaring Fork School District, the Third Street Center, and the Town of Carbondale, and technical partners including GreyEdge Group & NREL. This Coalition is working together to implement a district heating and cooling system powered primarily by geothermal energy. Key elements include detailed building energy modeling, retrofitting existing structures, and designing an ambient temperature loop to distribute energy across multiple facilities. Despite challenges such as regulatory uncertainty for thermal utilities and complex building retrofits, the project demonstrates the potential of geothermal systems to significantly reduce carbon emissions and enhance energy efficiency in cold climates. The case study serves as a model for integrating innovative clean energy solutions in community-scale applications, highlighting the importance of technical collaboration, community engagement, and sustainable design.

2. Background & Introduction

The Town of Carbondale is a home rule municipality located in Garfield County, Colorado. In its early days, Carbondale was known for its proximity to a coal mine which was closed in 1991 following a methane gas explosion. Located in a cold climate, most homes in Carbondale use natural gas for space and water heating. In 2017 the Town of Carbondale adopted a goal of creating a carbon-neutral community and achieving 100% reduction of carbon emissions by 2050, in addition to a 20% increase in energy efficiency over 2015 baseline by 2030 and obtaining 35–50% of energy from renewable sources by 2030.

Zero Energy Districts (ZEDs) were identified as one means of reaching these goals in the 2017 Carbondale Climate and Energy Action plan. Then, In 2018 the Carbondale Trustees asked Clean Energy Economy for the Region (CLEER) to explore the concept of creating a Zero Energy District in the Carbondale community. The scope of the project included:

- A scoping meeting/educational workshop to increase understanding of Zero Energy Districts and identify key issues and opportunities for locations in Carbondale
- Outreach to key stakeholders, property owners, residents and partners;
- Preliminary analysis and identification of main topics requiring additional technical assistance
- Identify steps for project development
- Identify and pursue near term and longer-term funding sources
- Connect with state and national resources working on ZEDs

An educational workshop was held on 17 May 2018 with Shanti Pless, a national leader on Zero Energy District development from the National Renewable Energy Laboratory (NREL) and Ed Mazria, Architecture 2030, considered one of the originators of the Zero Energy District concept. As part of the workshop a mini-charrette was held to consider specific locations in Carbondale that would lend themselves well to a zero energy district and identified key issues, opportunities, and barriers. The charrette identified an area centered around the Third Street Center as the best site for what’s now called the ThreeTwo Zero Energy District (32ZED) and is shown in Figure 1 and described in Table 1. The 32ZED currently produces 373 MWh/y of electricity from onsite and offsite PV with electrical consumption of 666 MWh/year and there is ample space within the 32ZED for increasing PV capacity to supply 100% of the current electrical load.

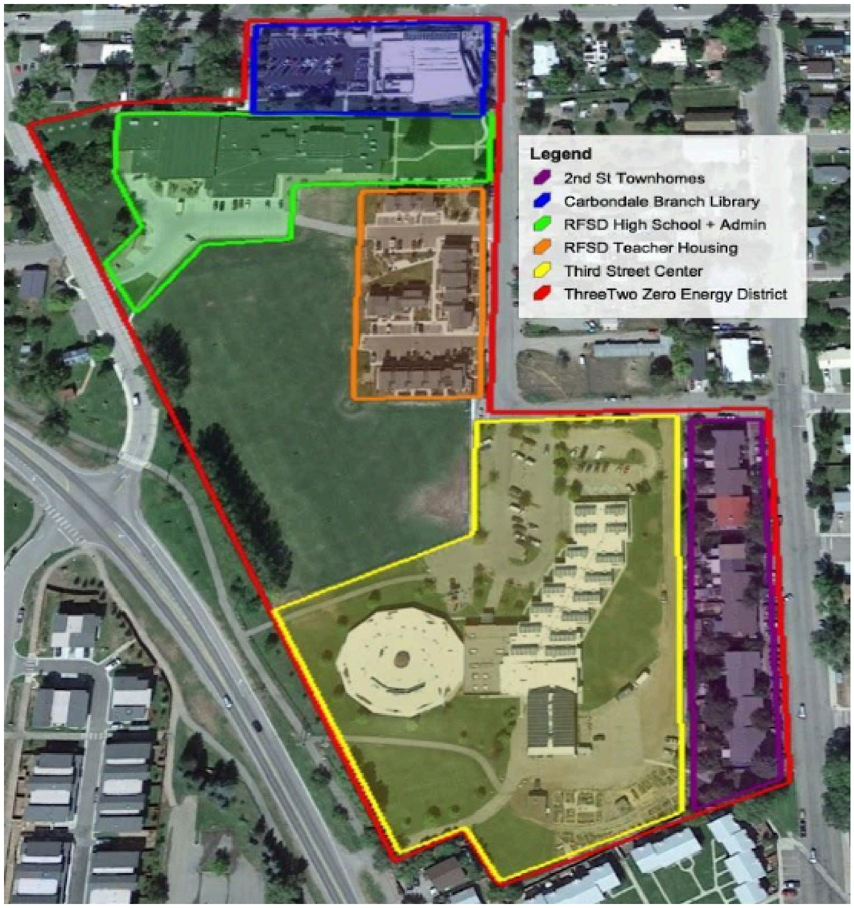


Figure 1: Layout of the Three-Two Zero Energy District

The Carbondale Community Geothermal Coalition was formed in response to the Department of Energy Office of Energy Efficiency and Renewable Energy Funding Opportunity Announcement #0002632 with the Geothermal Technologies Office entitled “Community Geothermal Heating and Cooling Design and Deployment.”

The Coalition comprises the Town of Carbondale, NREL, CLEER, Garfield Clean Energy, Third Street Center, the Roaring Fork School District, and the Garfield County Library District’s Carbondale Branch Library. The goal of the Carbondale Community Geothermal Coalition is to design, develop, and deploy a Thermal Energy Network (TEN) throughout the 32ZED in order to meet the decarbonization, resiliency, and air quality objectives of the Coalition. The build out of the TEN is envisioned to occur in two or more phases, with the first phase meeting 25% of the heating and cooling requirements and subsequent phases ultimately meeting the needs of the entire 32ZED.

3. Building information

To provide inputs for the building modeling task, the NREL team worked closely with CLEER to collect the required information about the buildings of the 32ZED. Five existing facilities in the district are candidates for inclusion in the 32ZED: Third Street Center, Second Street Townhomes (20 homes), Carbondale Branch Library, Roaring Fork School District (RFSD) Admin/Bridges High School, RFSD Teaching housing (20 units). Additionally, the team learned that the RFSD has plans to develop up to 70 additional staff housing units within the district, just north of the Third Street Center. For each building facility, the team collected pertinent information such as the building usage, vintage, geometry, square footage, energy efficiency levels, building system types, historical energy bills, etc. Below is a high-level building information summary table. For the new additional staff housing (*shown in italicized red*) it was assumed that the units would be designed to be all electric, and heated/cooled with ground source heat pumps connected to the TEN.

Facility	Capabilities/Resources	Square footage	Net Elec. (MWh/yr)	Annual Gas (MWh/yr)	Percent of District (gas)
Third Street Center	Built in 1961 with later additions. Retrofit in 2010. A net-zero electric building heated w/natural gas	45,100	-21	421	25.3%
Second Street Townhomes	Built in 1970s—20 townhome units, two stories & 1,500 sf, heated w/natural gas	28,144	107	302	18.2%
RFSD Admin / Bridges High School	Built in 1920's and 1980's with renovation in 2015, heated with natural gas	43,390	240	557	33.5%
Carbondale Branch Library	Built in 2013 w/PV on roof, heated with natural gas	13,000	84	205	12.3%
RFSD Staff Housing	Built in 2018—20 units in a mix of townhouses and flats, heated w/natural gas	22,378	259	180	10.8%
Potential Additional RFSD Housing	*Up to 70 additional units could be built to provide affordable housing for school district staff*	*78,375*	*517*	*N/A*	*N/A*
Total	**Mix of uses including education, public, non-profit commercial & affordable housing**	**230,387**	**1,186**	**1,665**	**100.0%**

Table 1: Buildings comprising the Three-Two Zero Energy District

A technical kickoff meeting was held at the Third Street Center in Carbondale, CO on November 16th, 2023 Participants included staff from CLEER, NREL, The GreyEdge Group, Third Street Center, New Energy Technologies, Panterra Energy, and other local stakeholders. The team discussed the project scope, milestones, workforce engagement, etc. Before the kickoff meeting, NREL's modeling lead, Dr. Jing Wang, conducted a site visit to the buildings to be modeled and collected first-hand information about the buildings. See Figure 2 below for a picture of the kickoff meeting.

Figure 2: Team kickoff meeting at the Third Street Center

4. Building Modeling

The building modeling effort utilized the URBANopt District Energy System (UO DES) capability. The annual building energy profiles were first generated in UO and then exported into a DES model in Modelica for detailed district energy modeling. Two scenarios were modeled: the baseline scenario and the retrofit scenario. The baseline scenario simulated the existing buildings as they currently are, and validated the modeling results against the collected historical building energy bills. This step assures the accuracy of the baseline models and provides the foundation for building retrofitting studies. The retrofit scenario modeled the building with potential upgrades such as energy efficiency upgrades or HVAC system replacement. To accommodate the district ambient-temperature loop (ATL), the existing building HVAC systems will be replaced by water-source heat pumps to provide heating and cooling to the spaces.

Whole-building energy sensors from Copper Labs were installed to measure electricity and gas usage needed for future modeling and control studies. Copper Labs energy sensors can remotely access data from a wide range of existing electric, gas, and water meters (including both drive-by AMR and “smart” AMI meters).

5. Geothermal Loop Modeling & Design

The work on the geothermal loop modeling focused on conducting the test borehole drilling and planning for technical details of the district loop modeling. The test borehole was drilled in the open space behind the Third Street Center. During the drilling, sample cuttings were collected to determine the local soil thermal conductivity and diffusivity. The tests found the ambient earth temperature was around 58°F, which was a promising number showing the ground was sufficient for a geothermal system.

The 8760-hour building heating and cooling load profiles obtained from the building modeling informed the geothermal heat exchanger sizing. The district ATL will comprise a one-pipe central primary loop and two-pipe loops supplying and returning fluid to and from buildings and other thermal assets. The whole geothermal loop system will be operated following a hierarchical order. First, buildings will prioritize balancing their own heating and cooling needs. Second, once the building loop temperature exceeds a certain range, it will begin exchanging heat with the central ATL. The ATL will control the variable speed pump to maintain a design temperature range. Third, if the loop temperature falls out of range, the geothermal heat exchanger will be activated to serve as a source/sink for the loop. Last, additional thermal assets such as a greywater heat recovery system and/or the solar thermal water heater can also be brought online to provide further heating/cooling to the central loop if needed. The modeling of this hierarchical operation can be achieved using Modelica.

6. Test Drill and Thermal Response Test

A 48.9-hour in-situ advanced thermal conductivity test was performed on November 2–30th, 2023. The test was performed at the borehole drilled on November 16–20th, at the Third Street Center at 520 S. 3rd Street in Carbondale, Colorado 81623. Testing was done with a certified Ewbank portable test unit. Figure 3 shows a photo taken during the test drilling.

Figure 3: Test drilling outside the Three Street Center in the Three-Two Zero Energy District in November 2023 (Photo credit: Aaron Orelup, GreyEdge Group)

The borehole was 5-5/8 inches in diameter and 449 feet in depth. A 1-1/4 inches SDR-11 4710 HDPE loop was installed in the borehole and grouted with graphite enhanced bentonite grout to the surface. The average deep earth temperature was 56.3°F, which indicates the average undisturbed deep earth temperature. The power input was 17.45 Watts per foot of borehole. This test data was acquired under the recommendations of the International Ground Source Heat Pump Association (IGSHPA) and the American Society of Heating, Refrigeration, and Air conditioning Engineers (ASHRAE). The line source method was used to determine the thermal conductivity. The results of the thermal response test are summarized in Table 1.

Table 1: Summary of the thermal response test results

Description	Ground	Grout	Units
Thermal Conductivity	1.66	1.30	BTU/ft-hr-°F (TC or K)
Volumetric Heat Capacity	22.7	37.0	BTU/ft^3-°F (HC)
Deep Earth Temperature (avg)	56.8°F		
Calculated Diffusivity	1.76		ft^2/Day

The thermal response test shows that there is a significant thermal conductivity impact from water movement most likely in the top 120 feet of unconsolidated soils in the Carbondale valley. This upper layer creates a thermal transfer opportunity which a ground heat exchanger (GHE) designer could perhaps more significantly utilize. The dynamic volumetric movement situation in that layer creates higher calculated diffusivity and overall calculated volumetric heat capacity figures than a conventional well log based analysis. Figure 4 shows the entire 48+ hour test data in blue with intentional power fluctuations after 36 hours to allow drawing more accurate conclusions about the grout and ground properties. The thermal response test numerical analysis results are shown in green, which almost exactly covers the blue collected data, showing the accuracy of the numerical analysis.

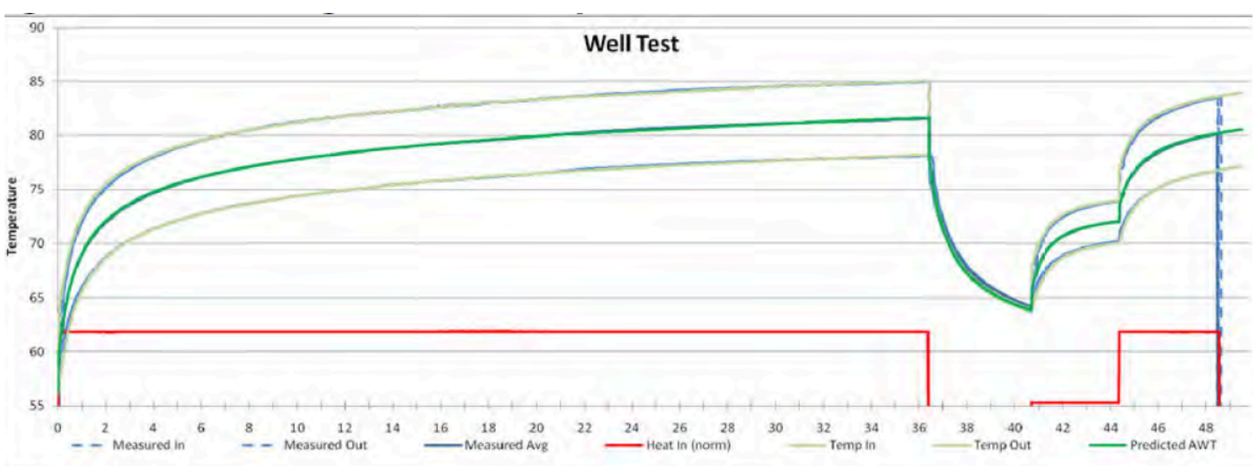
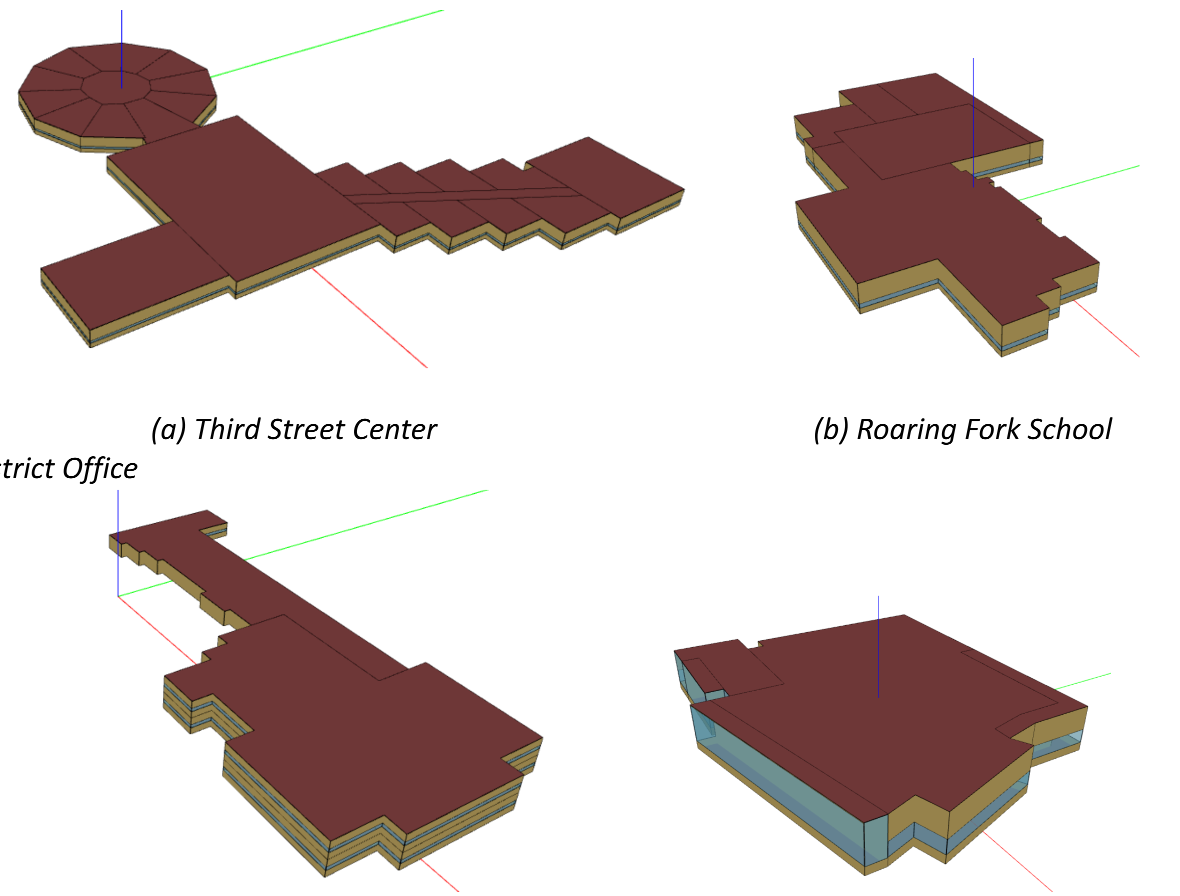


Figure 4: Thermal response test measured data and numerical analysis results.

7. Building Energy Modeling & Calibration

As shown earlier in Figure 1, the 32ZED, located near downtown Carbondale, CO, comprises (from bottom right to top left) the Second Street Townhomes, the Third Street Center, 20 affordable housing units for teachers, Bridges High School and Roaring Fork School District's Carbondale Office, and the Carbondale Branch Library. Future extension of this district also includes up to 70 additional dwelling units that could be built to provide affordable housing for school district staff.

Based on the building information collected, the NREL team completed the energy modeling of all buildings of the 32ZED. URBANopt was used to generate the initial building models based on the DOE prototypical building models. Figure 5 shows the 3D views of the OpenStudio models of the Third Street Center, Roaring Fork School District (RFSD) Office, Bridges High School, and Carbondale Branch Library as examples.



(a) Third Street Center *(b) Roaring Fork School District Office*

(c) Bridges High School *(d) Carbondale Branch Library*

Figure 5: 3D view of the OpenStudio model of Third Street Center.

Next, a detailed monthly energy model calibration was performed for existing buildings using monthly utility bills. ASHRAE Guideline 14 recommended metrics for monthly energy calibration were used to evaluate the models. For instance, the Normalized Mean Bias Error (NMBE) for monthly energy calibration should be between -5% and 5%; the Coefficient of Variation of the Root Mean Square Error (CVRMSE) should be within the range of 0–15%. For existing buildings without historical utility data, we adjusted the building models based on engineering judgment to match an annual gas energy usage intensity (EUI). Table 2 summarizes the energy model calibration results. The historical annual gas EUI for Second Street Townhomes was estimated from the utility bills of one middle unit as we were not able to obtain bills from other homeowners. Further, the gas EUI for RFSD Staff Housing is estimated based on Residential Energy Consumption Surveys (RECS) data for cold climate homes built in the 2010s. Therefore, the simulated gas EUI for Second Street Townhomes and RFSD Staff Housing are slightly deviated from these estimates. From the table, we see that for those buildings that were calibrated towards monthly bills, the NMBE and CVRMSE all lie within the ASHRAE Guideline 14 range mentioned above.

Table 2: Summary of building energy model calibration results.

Building	Floor Area (sf)	Historical Annual Gas EUI (kBtu/sf)	Simulated Annual Gas EUI (kBtu/sf)	EUI Relative Deviation (%)	Monthly Gas Calibration	NMBE (%)	CVRMSE (%)
Third Street Center	45,100	31.9	31.2	-2.2	Yes	-2.4	5.5
Second Street Townhomes	28,144	33.5	35.5	6.0	Yes	0.7	12.3
			38.2	14.0	Yes	-2.0	11.4
			37.6	12.2	Yes	-0.5	12
RFSD Office / Bridges High School	43,390	43.8	41.5	-5.3	No	N/A	N/A
Carbondale Branch Library	13,000	58.4	56.4	-3.4	Yes	-3.5	11.9
RFSD Staff Housing	33,000	25	21.6	-13.7	No	N/A	N/A
			21.9	-12.3			
			18.9	-24.6			
			17.5	-30.1			

8. Initial Geothermal Loop Design

The 8760-hour building heating and cooling coil load profiles obtained from the building modeling were used to inform the district loop design by GreyEdge. The district ambient temperature loop (ATL) will comprise a one-pipe central primary loop and two-pipe loops supplying and returning fluid to and from buildings and other thermal assets. The initial design from The GreyEdge Group considers the GHE as a heat source/sink for the loop. Figure 6 shows the initial loop design that consists of six subfields, each with 15 boreholes for a total of 90 bore holes) surrounding the Third Street Center. The borehole pipes will be 1.25-inch HDPE pipes. Details of the design were reviewed and discussed by the technical team in a design charrette held on 3 April 2024.

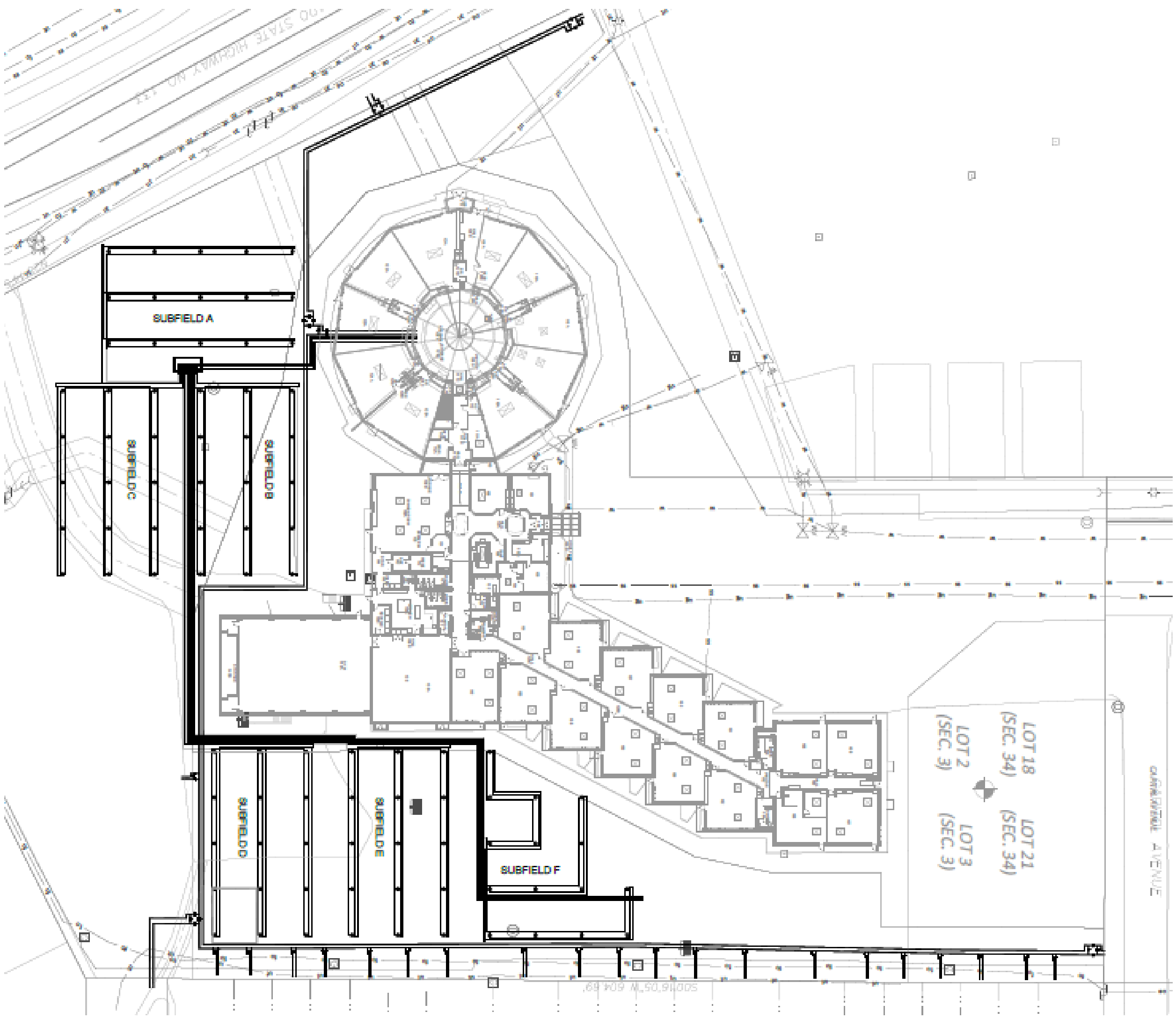


Figure 6: Initial design of the district loop consisting of six subfields of borehole fields.

This initial GreyEdge ATL design utilizes a hybrid configuration with the existing gas boilers plus solar thermal being used to cover peak heating loads. The results of GreyEdge's design & analysis are shown in Table 3.

Table 3: Ambient temperature loop & GHX design loads.

	COOLING		HEATING	
Peak Loads	**kW**		**kW**	
Geo HX	159.3	100.0%	100.0	25.0%
Hybrid (Boilers + Solar HX)	0.0	0.0%	300.1	75.0%
Total Peak (kW)	**159.3**	**100.0%**	**400.1**	**100.0%**
Total Loads (annual)	**MWh**		**MWh**	
Geo HX	55.7	100.0%	399.4	69.6%
Hybrid (Boilers + Solar HX)	0.0	0.0%	174.7	30.4%
Total (MWh)	**55.7**	**100.0%**	**574.1**	**100.0%**

At that design charrette, the team decided to explore the possibility of additional thermal assets such as a wastewater heat recovery system and an expanded solar thermal heating system that could connect to the ATL to provide further heating to the buildings if needed. These additions could contribute additional thermal energy and thereby increase the system efficiency while reducing the size of the bore field. The sizing of the central loop was also discussed as it needs to be robust enough, taking into account potential future connections of more buildings into the loop.

A concept diagram of the initial and future district loop design is shown in Figure 7, involving all buildings and thermal assets. The Initial Phase shown on the left hand side includes the Third Street Center as building 1 and several Second Street Townhomes as buildings 2–4 (note: there are 20 total townhomes). The right hand side includes anticipated Future Development of the ATL with an additional ground heat exchanger and a waste heat recovery element added into an expanded ATL along with additional buildings being connected. Note that the concept diagram is meant for illustrating the design concept only and does not reflect the actual topology of the district geothermal loop designed by The GreyEdge Group.

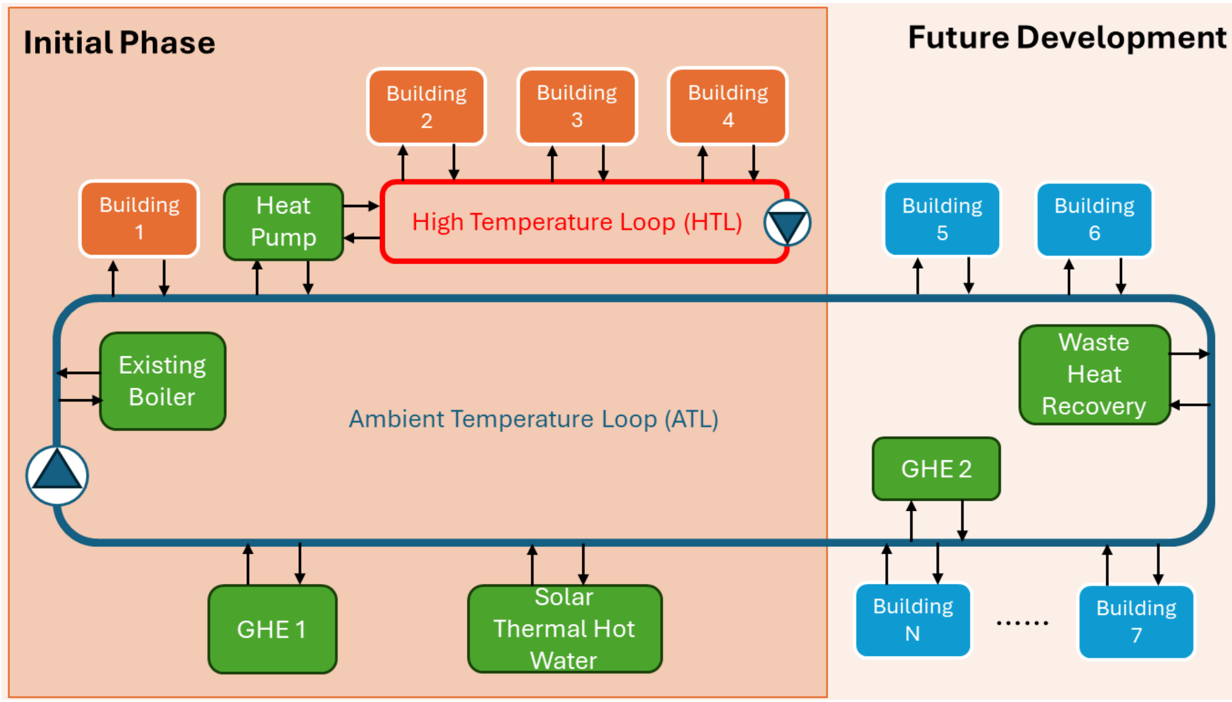


Figure 7: Concept diagram of the district geothermal loop (for illustration purpose only).

9. Utilizing GTO's URBANopt Geothermal Heat Pump Model

The modeling of the district loop was accomplished by utilizing the GTO funded URBANopt GHP capability. In this new capability, every step is streamlined and automatic, from the sizing of the GHE to the generation and simulation of the district loop model. To utilize this capability, the NREL team collected sizing and modeling inputs (as shown in Table 4) from the project team. Once the sizing from the URBANopt GHP workflow is done, it was compared to the initial design from GreyEdge, to serve as a validation of the GHP sizing tool. The comparison showed that the GHE size from the URBANopt workflow (112 boreholes of 97.64 m depths) is slightly smaller than the GreyEdge size (90 boreholes of 136.86 m depths), which could be attributable to various factors such as different sizing assumptions and sizing algorithms.

Table 4: Sizing and modeling input collection table for the URBANopt GHP workflow.

Group	Parameter name	Description	Type	Default	Unit	Default (IP unit)	IP unit	Note
Building ETS	cop_heat_pump_heating	COP of heat pump for heating water production	Number	2.5	N/A	2.5	N/A	For sizing
	cop_heat_pump_cooling	COP of heat pump for cooling water production	Number	3.5	N/A	3.5	N/A	For sizing
Fluid	fluid_name	Circulation fluid type	Select from list: "WATER", "ETHYLALCOHOL", "ETHYLENEGLYCOL", "METHYLALCOHOL", "PROPYLENEGLYCOL"	"WATER"	N/A	"WATER"	N/A	
	concentration_percent	Mass fraction concentration percent of circulation fluid. '0' indicates pure water; '20' indicates 20% antifreeze, 80% pure water.	Number	0	%	0	%	
Grout	conductivity	Thermal conductivity of the borehole filling material	Number	2.248	W/(m-K)	1.3	BTU/(ft-hr-°F)	From TRT report
	rho_cp	Volumetric heat capacity of the borehole filling material	Number	1378581	J/(m3-K)	37	BTU/(ft3-°F)	From TRT report

Group	Parameter name	Description	Type	Default	Unit	Default (IP unit)	IP unit	Note
Soil	conductivity	Thermal conductivity of the soil material	Number	2.871	W/(m-K)	1.66	BTU/(ft-hr-°F)	From TRT report
	rho_cp	Volumetric heat capacity of the soil material	Number	845778	J/(m3-K)	22.7	BTU/(ft3-°F)	From TRT report
	undisturbed_temp	Undisturbed soil temperature	Number	13.8	degC	56.8	degF	From TRT report
Pipe	inner_diameter	Inner diameter of the pipe	Number	0.034036	m	1.34	inch	1-1/4'' DR-11 HDPE
	outer_diameter	Outer diameter of the pipe	Number	0.042164	m	1.66	inch	1-1/4'' DR-11 HDPE
	shank_spacing	Shanking spacing, the distance between the outer surfaces of the pipes, not referenced from center.	Number	0.018557	m	0.7306	inch	(BH Dia - 2 * Pipe O.D.) / 3
	roughness	Surface roughness of pipe	Number	1.00E-06	m	3.94E-05	inch	
	conductivity	Thermal conductivity of the pipe material	Number	0.4	W/(m-K)	0.23	BTU/(ft-hr-°F)	
	rho_cp	Volumetric heat capacity of the pipe material	Number	1542000	J/(m3-K)	41.4	BTU/(ft3-°F)	

Group	Parameter name	Description	Type	Default	Unit	Default (IP unit)	IP unit	Note
	arrangement	Pipe arrangement specified	Select from list: "SINGLEUTUBE", "DOUBLEUTUBESERIES", "DOUBLEUTUBEPARALLEL"	"SINGLEUTUBE"	N/A	"SINGLEUTUBE"	N/A	
Simulation	num_months	Number of sizing simulation months	Number	240	months	240	months	
Geometric constraints	b_min	Minimum borehole-to-borehole spacing	Number	3	m	9.84	ft	
	b_max	Maximum borehole-to-borehole spacing	Number	10	m	32.81	ft	
	max_height	Maximum height, or active length, of each borehole heat exchanger	Number	135	m	442.91	ft	
	min_height	Minimum height, or active length, of each borehole heat exchanger	Number	60	m	196.85	ft	
	method	Design algorithm specified	Select from list: "NEARSQUARE", "RECTANGLE"	"RECTANGLE"	N/A	"RECTANGLE"	N/A	

Group	Parameter name	Description	Type	Default	Unit	Default (IP unit)	IP unit	Note
Design	method	Ground load calculation method	Select from list: "AREAPROPORTIONAL", "UPSTREAM"	"AREAPROPORTIONAL"	N/A	"AREAPROPORTIONAL"	N/A	
	flow_rate	Volume flow rate	Number	0.5	L/s	7.93	gpm	
	flow_type	Indicates whether the design volumetric flow rate set on a per-borehole or system basis	Select from list: "BOREHOLE", "SYSTEM"	"BOREHOLE"	N/A	"BOREHOLE"	N/A	
	max_eft	Maximum heat pump entering fluid temperature	Number	35	degC	95	degF	Can iterate later
	min_eft	Minimum heat pump entering fluid temperature	Number	5	degC	41	degF	Can iterate later
Geometric parameters	length_of_ghe	Horizontal length of property boundary defining surface area available for ground heat exchanger	Number	113.46	m	372.24	ft	Placeholder
	width_of_ghe	Horizontal width of property boundary defining surface area available for ground heat exchanger	Number	99.03	m	324.90	ft	Placeholder
Borehole	buried_depth	Borehole buried depth	Number	2	m	6.56	ft	

Group	Parameter name	Description	Type	Default	Unit	Default (IP unit)	IP unit	Note
	diameter	Diameter of the borehole	Number	0.14	m	5.51	inch	
	length_of_boreholes	Height of the boreholes, to be sized	Number	136.86	m	449	ft	
	number_of_boreholes	Total number of boreholes, to be sized	Integer	90	N/A	90	N/A	

10. Building Retrofit Modeling

The retrofitted building HVAC systems will consist of unitary water-source heat pumps connected to the central district loop to provide both heating and cooling. We modeled the retrofitted systems using the Modelica language, namely, the Modelica Buildings Library (MBL) developed by LBNL. The annual building heating and cooling loads were generated from the calibrated building energy models to inform the retrofit modeling.

Each building system model is composed of two sub models. The first is an energy transfer station (ETS) model, which contains heating and hot water heat pumps and cooling heat exchangers to harvest heating and cooling from the district water loop. Heating heat pumps supply water between 28°C and 38°C, and cooling heat exchangers supply water between 21°C and 23.6°C. Because we expect heat pumps to provide cooling in the actual Carbondale geothermal district system, we calculated cooling heat pump compressor input power for the given building loads during simulation result post-processing.

The second is a building model that contains fan coil units, input building heating and cooling loads, and controls to regulate building temperature. In each building system model, water from the district loop is pumped through the ETS and transfers heat to or from separate water loops. The water in those loops is then pumped through the building model to provide heating, hot water, and cooling. The building system model is shown in Figure 8 below, where light blue lines connecting the models represent fluid flow, and dark blue lines show signal flow.

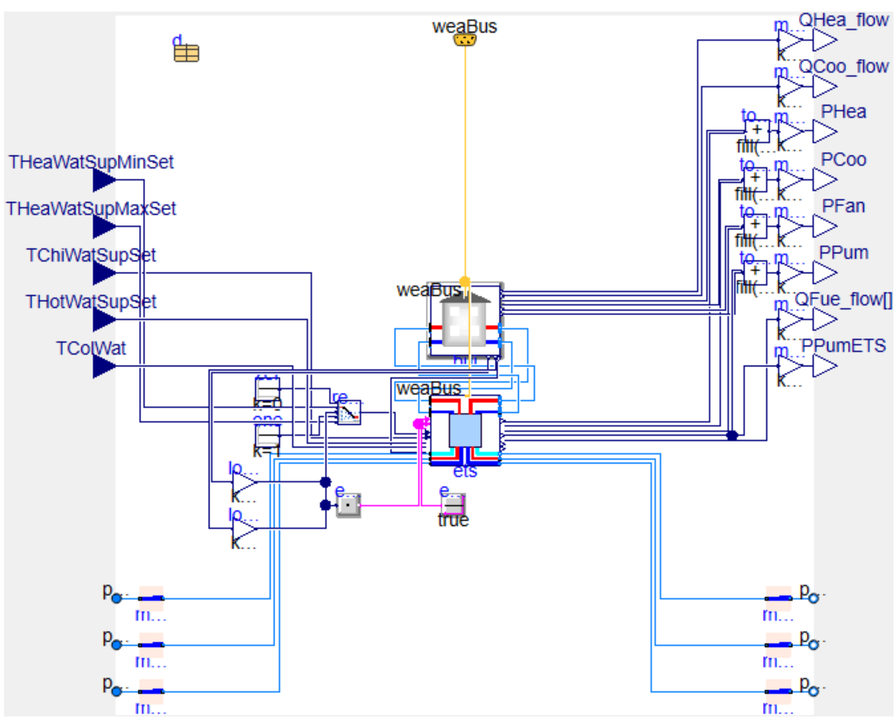


Figure 8: Building System model with energy transfer station (ETS) and building model (above ETS).

11. Geothermal District Loop Modeling

Based on the system design, the district loop will be a one-pipe loop that connects to the geothermal heat exchanger (GHE) and the building heat pumps. A central distribution pump circulates the fluid in the district pipe through a closed-loop geothermal borefield and four buildings connected in series. The district energy system model can be seen in Figure 9.

The district pump (shown as "pumDis" in Figure 9) operates by maintaining a minimum pump mass flow as long as the temperature of the loop is within an acceptable range. When the temperature reaches a certain number of degrees from the minimum or maximum allowed temperatures, the pump increases mass flow to bring the temperature back into the acceptable range. The four building models shown connected to the loop are described in depth in Section 7, Building Energy Modeling & Calibration.

The borefield model splits the flow from the main distribution pipe into 90 geothermal boreholes. Heat is gained or lost in the boreholes according to the internal resistance of the borehole, whose values depend on parameters such as length of the borehole, heat capacity of filling material, and thermal resistances between different parts of the borehole. The heat transfer between the borehole and the soil is calculated using a cell-shifting load aggregation technique (Claesson & Javed, 2012).

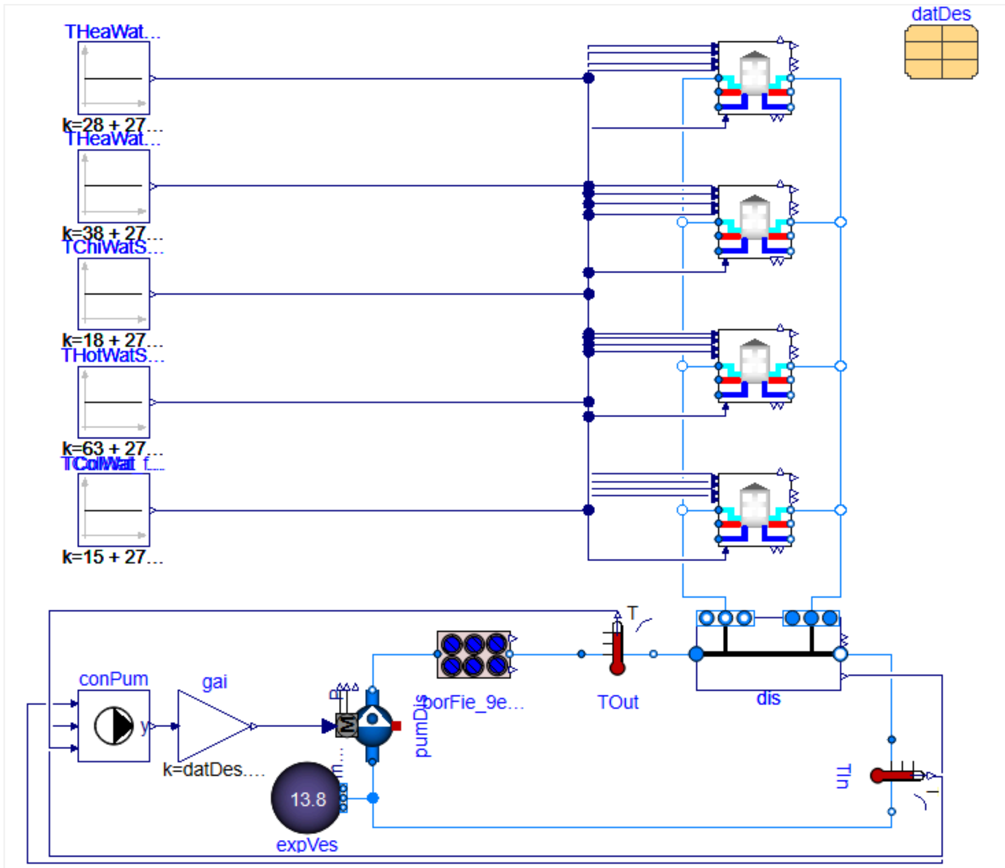


Figure 9: District energy system model with main district pump and distribution loop.

12. Simulation Result Analysis

Based on an annual simulation of the geothermal district system in Modelica, we analyzed the energy and emissions reduction potential in comparison to the original building systems with and without PV generation. Both heating and cooling energy were simulated in the conventional and district energy cases, but the actual conventional system does not have a cooling system. Therefore, while we present cooling energy use for the 5G system, only heating is compared in this section to accurately depict energy use differences between the conventional and district energy system.

Analyses were conducted with and without on-site PV electricity generation. Monthly PV electricity generation data provided by utilities for two PV systems (titled “current” and “new”) at the Third Street Center were used to generate hourly data in PVWatts. PVWatts is an NREL-developed online resource that estimates PV system energy generation using location and PV system parameters (Dobos, 2014). The current system is a 52.8 kW system facing South with a 30° tilt, and the new system is a 50.86 kW system with half of the panels facing East and half facing West, both with 23° tilts. Using these parameters, hourly PVWatts data were used to calculate the amount of electricity needed from the grid at each hour of the year.

Site heating energy use was found through summing the energy uses of all equipment in the district energy systems and conventional systems and categorizing according to energy type, which in this case was either electricity or natural gas. PV generation was subtracted from site electricity use on an hourly basis. Source heating energy was then calculated by applying site to source conversions for each of the site energy uses. The site to source conversions used for natural gas and electricity are 1.048 and 3.167, respectively, and were obtained from EnergyPlus simulation outputs. It was found that the 5G district energy system used 27% of the heating site energy and 69% of the source energy that the conventional system required without PV. The district energy system saves source energy despite being reliant on electricity, which has around three times as many losses as natural gas from source to site, because the heat pumps used in the system consistently operate at coefficients of performance (COP) above the level required to compensate for energy losses associated with electricity generation, transmission, and distribution.

Figure 10 below shows a monthly breakdown of energy use for the district energy system, denoted in the legend as “5G”, and the conventional system, denoted in the legend as “current”, with and without PV generation. Energy use associated with fans, pumps, and ‘heat’, which refers to the natural gas used in the boilers for the conventional system and the electricity used for heat pump compressors in the district energy system, are differentiated.

The conventional fan and pump energy included in the heating analysis include fan and pump energy used for cooling. Because Carbondale is a heating dominated region, including cooling fan and pump energy is not expected to inflate total energy use significantly; however, heating fan and pump energies are slightly overestimated in this analysis.

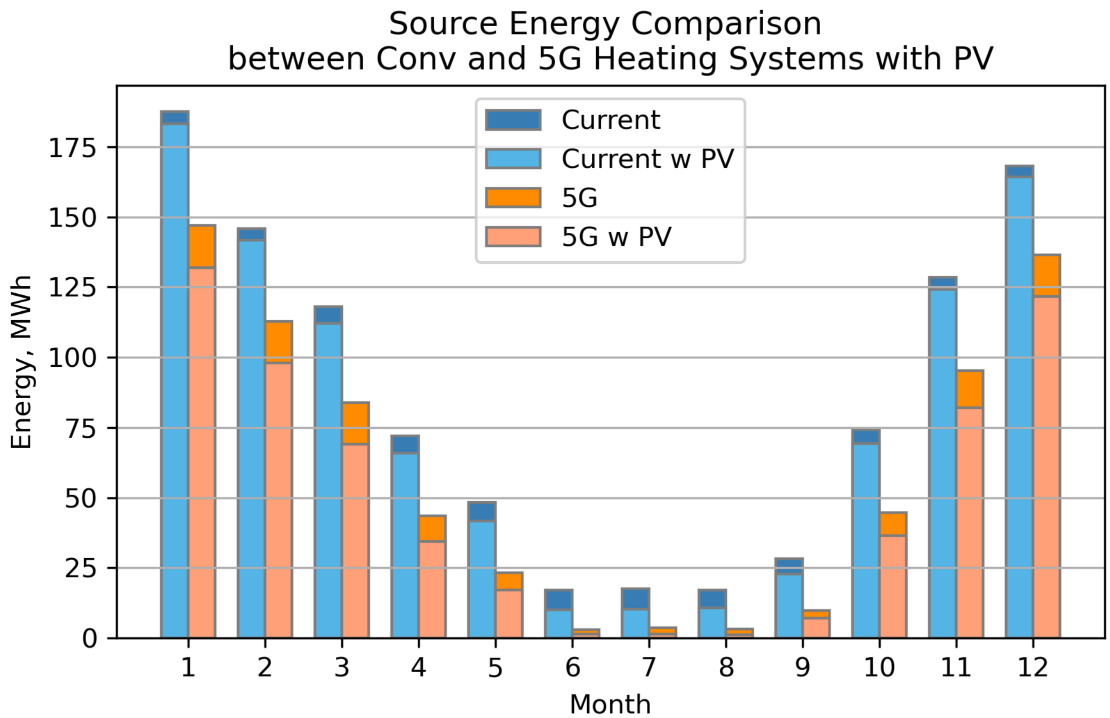


Figure 10: Annual source energy use comparison between conventional and 5G district heating systems.

Monthly cooling energy use associated with the 5G district cooling system heat pumps, fans, and pumps is shown in Figure 11 alongside all other conventional and 5G system equipment energy demands. Because Carbondale is such a heating-dominated region, energy use for the cooling system is very small compared to the overall 5G system energy use.

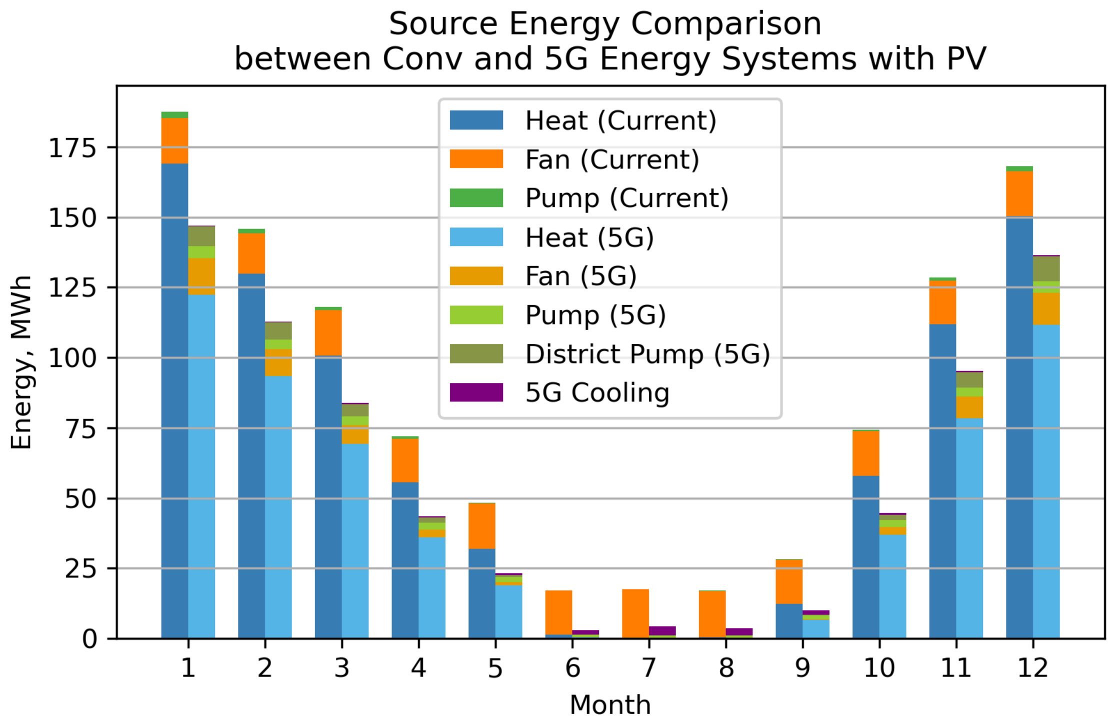


Figure 11: Monthly source energy use by equipment type for conventional and 5G systems.

Carbon emissions for the conventional and district energy systems were then compared for site energy. Electricity carbon emissions used WattTime's 2022 marginal operating emission rate for the Public Service of Colorado (PSCO) region, which is the carbon emission rate of grid electricity generators considering electricity imports and exports, renewable curtailment, and energy generators' responses to changes in electricity demand (WattTime, 2022). Transmission losses of 5.1% are also applied per the EPA's 2022 eGRID summary tables for the RMPA region (EPA, 2022). Natural gas carbon emission rates use URBANopt's rate of 187.7 kg/MWh. EnergyPlus's natural gas site to source conversion is used to consider energy needed to transport natural gas on-site.

A monthly breakdown of carbon emissions for the conventional and district energy system is shown in Figure 12. The district energy system emits about two thirds (67%) of the CO_2 that the conventional system emits in a year without PV and about 61% with PV. This is estimated to translate to 61 metric tons of CO_2 saved per year without PV, and 65 metric tons with PV. The district energy system is able to utilize more PV generation than the conventional system because it relies more heavily on electricity for its energy needs.

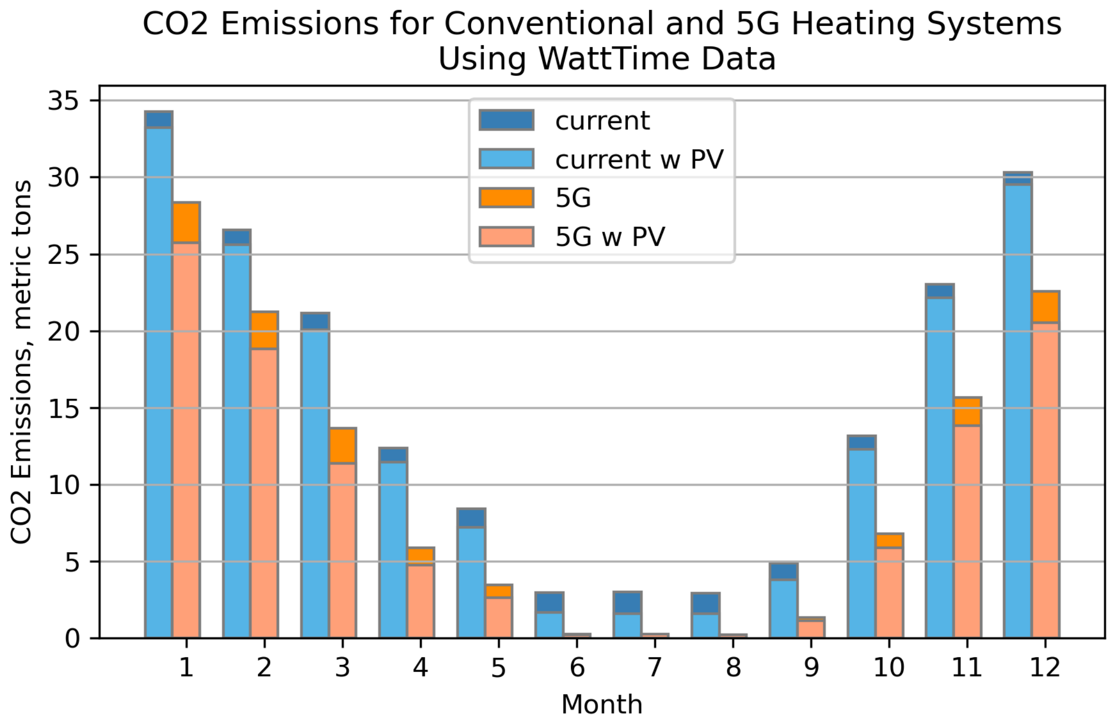


Figure 12: Annual carbon emission comparison between conventional and 5G district energy systems without installed PV integration.

The tables below summarize our findings on site and source energy use and carbon emissions for the conventional and 5G district heating systems with and without PV systems. Compared to the conventional system without PV, **the 5G system can save up to 77% site electricity, 41% source electricity, and 43% carbon emissions.**

Table 4: Site Energy Usage for Conventional and District Heating Systems with and without PV.

	Total Natural Gas (MWh)	Total Electricity (MWh)	Total Energy (MWh)	% decrease from conventional, no PV
Conventional, no PV	758	64	821	N/A
5G, no PV	0	220	220	**73**
Conventional, PV	758	38	796	3
5G, PV	0	190	190	**77**

Table 5: Source Energy Generation for Conventional and District Heating Systems with and without PV.

	Total Natural Gas (MWh)	Total Electricity (MWh)	Total Energy (MWh)	% decrease from conventional, no PV
Conventional, no PV	822	201	1023	N/A
5G, no PV	0	707	707	**30**
Conventional, PV	822	135	956	7
5G, PV	0	601	601	**41**

Table 6: Carbon Emissions for Conventional and District Heating Systems with and without PV.

	CO2 Emissions from Natural Gas (metric tons/yr)	CO2 Emissions from Electricity (metric tons/yr)	Total CO2 Emissions (metric tons/yr)	% decrease from conventional, no PV
Conventional, no PV	149	34	183	N/A
5G, no PV	0	122	122	**33**
Conventional, PV	149	21	170	7
5G, PV	0	105	105	**43**

In addition to current carbon emissions, we analyzed future carbon emissions of the conventional and district energy system using Cambium carbon emission rates. Cambium is an NREL-supported database that estimates electric grid-generated carbon emissions through 2050 based on eight possible U.S. decarbonization scenarios (Gagnon et al., 2024). This analysis used Cambium's long-run marginal emission rate (LRMER) metric, which estimates grid CO_2 emissions considering future grid infrastructure change. The LRMER metric was chosen among other metrics in Cambium, such as short-run marginal emissions rates (SRMER) and average emission rates (AER) because it considers future infrastructure change and electrical grid dynamics, such as sudden increases and decreases in demand (Gagnon & Cole, 2022). It also considers transmission losses (Gagnon, 2024).

The four scenarios analyzed include: ***midcase***, the base case of Cambium in which no new technologies are considered, no new energy policies after September 2023 are implemented, and demand, energy, and technology costs are average projections; ***decarb2030***, in which the electric grid fully decarbonizes by 2030; ***highNGprice***, in which the midcase has higher natural gas prices; and ***highREcost***, in which the midcase has higher renewable energy costs.

Site electricity was multiplied by the LRMER associated with each of the four chosen Cambium scenarios for 5-year increments from 2025 to 2050. Natural gas carbon emissions calculated in Figure 12 above are added for total system carbon emission forecasts. As can be seen below in Figure 13, emissions from the district energy system are forecasted to drop significantly more than the conventional system for all analyzed scenarios because of its higher electricity use and the grid electricity becoming cleaner. Furthermore, carbon emissions for the 5G system plateau between zero and 25 metric tons of CO_2 per year by 2050, whereas the conventional system plateaus around 150 metric tons of CO_2 per year by 2050 due to its reliance on natural gas.

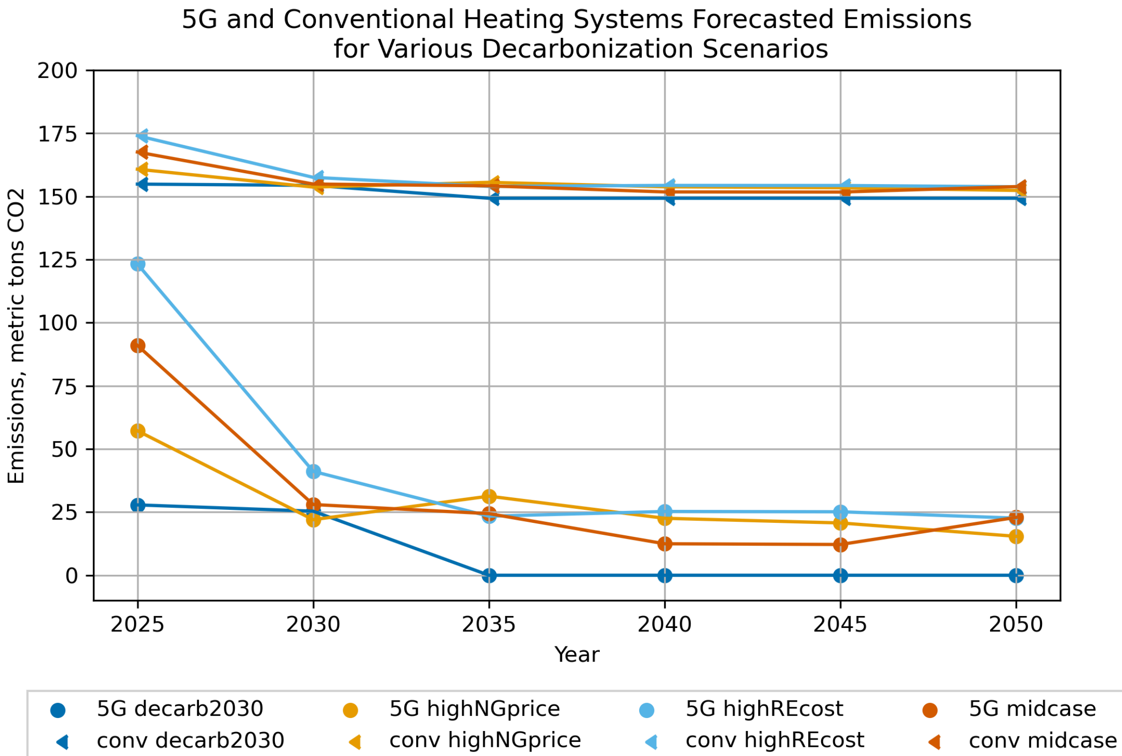


Figure 13: Forecasted carbon emissions of conventional and 5G district energy systems using Cambium carbon emission rates from 2025–2050 and considering current PV capacity.

13. Community Engagement: Design Charrette, TENs Workshop, & Open House

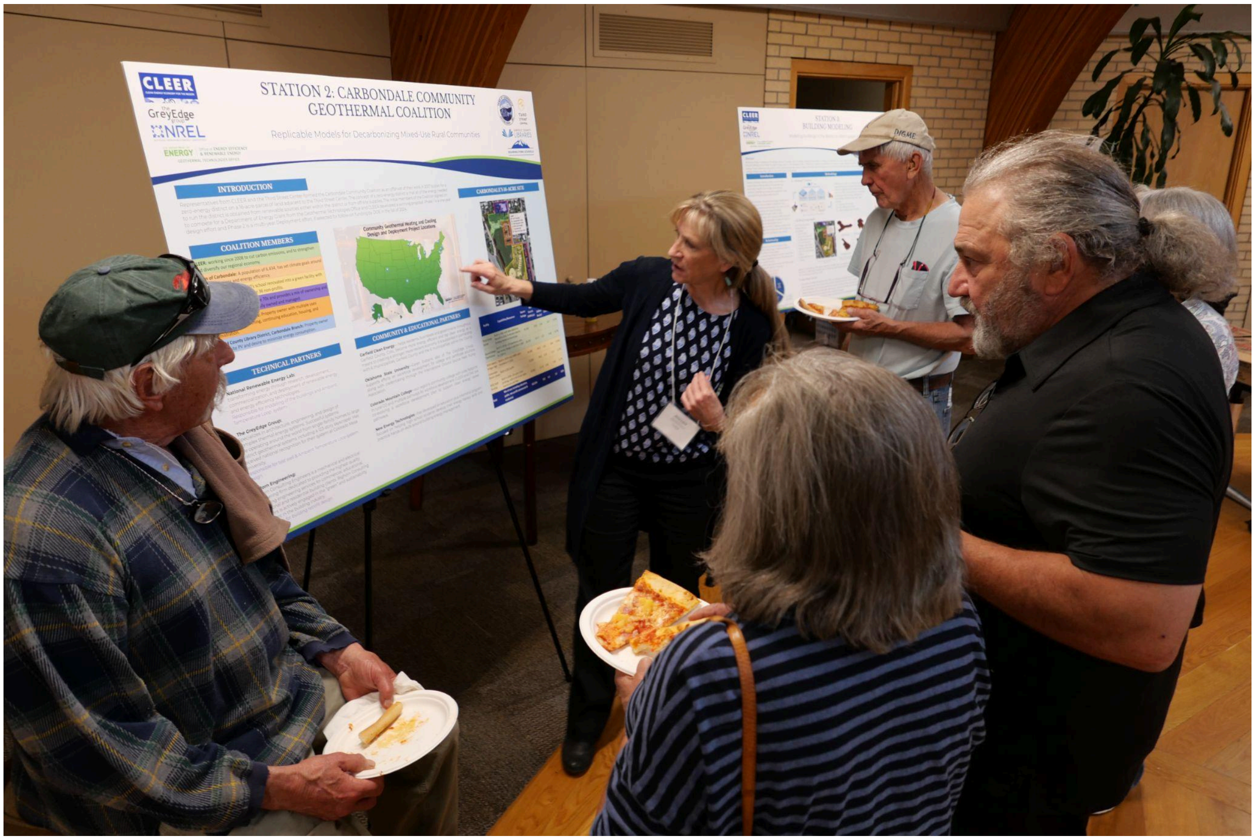
CLEER and the coalition partners held a technical team Design Charrette, Thermal Energy Network Workshop and Community Open House at the Third Street Center, all on April 24th. The design charrette included staff from Bighorn Engineering who also toured the Third Street Center and one of the Second Street Townhomes with CLEER, NREL and GreyEdge staff. Additionally, the technical team reviewed NREL's initial building and 5G modeling results and discussed options for the geo bore field location and mechanical room options.

The workshop was entitled “the Heat Beneath our Feet” to build on the messaging endorsed by the Colorado Energy Office and Governor Jarid Polis’ administration in alignment with DOE GTO’s goals of educating communities about the promise of geothermal resources. The audience for the workshop included community members and professionals (such as planners, educators, engineers, architects, public officials, general contractors, developers, etc.). The Third Street Center’s Calaway room was standing room only with approximately 100 registered attendees. The purpose was to advance the awareness around thermal energy networks and the need for workforce development to support their scaling throughout our region. CLEER also presented to a Colorado Mountain College class on sustainability to advance the awareness of thermal energy networks and support the project's workforce development goals. PI Jon Fox-Rubin presented on the overall GTO project goals and initial project insights, while Matt Garlick from GreyEdge, presented on the merits of 5G Ambient Temperature Loops. NREL’s PI Xin Jin spoke about DOE’s decarbonization goal and how geothermal technologies can accelerate it. Jing Wang presented NREL’s modeling tool URBANopt for district energy system planning and modeling. Dr. Bryan Hannegan, President of Holy Cross Electric (and former NREL staff member), presented the promise of TENs to decarbonize not just buildings but also electrical grids. Bryce Carter, Project manager from the Colorado Energy Office, sat on a panel along with utility and industry experts on the workforce challenges in our region and opportunities for collaboration to develop geothermal projects.

Figure 14: NREL team presenting at the Thermal Energy Networks Workshop.

An Open House was held after the workshop so participants and community members who couldn’t attend the workshop could learn more about 1) the role that Thermal Energy Networks can play in decarbonizing communities, 2) the Carbondale Community Geothermal Coalition, 3) the Three-Two Zero Energy District and initial design considerations, and 4) Building and Geo-loop modeling by NREL. There was also a poster eliciting feedback from participants. The event was designed to be family friendly with food and support from the Aspen Science Center, which provided hands-on experiential games for children (and adults) to experience, first hand, heat transfer capabilities of water. Copies of the posters are available at the GDR.

Figure 15: Example Open House Posters Station for Community Engagement



14. Retrofit Design Considerations

The Retrofit design team explored a wide variety of options for both the Third Street Center and the Second Street Townhomes. We'll cover the Third Street Center first, as it was more straightforward despite it being an older commercial building that was built in stages starting in 1962. The reason is that the team decided to "abandon in place" the existing heating system and bring individualized control to each space. The key reasons for this are that 1) each "old classroom" space in the school building has a different tenant and occupancy, 2) Some of the spaces have ample solar gain from windows and south facing walls, and thereby need cooling in the summer, while other spaces are north facing and have higher heating requirements, and 3) this approach allows for individualized control and integrated air handling for improved indoor air quality. The team believes that the requisite electric service upgrades will be achievable along with the installation of an internal ambient water loop for the unitary water to air heat pumps to run off of. See Figure 16 below for the various zones as designed for.

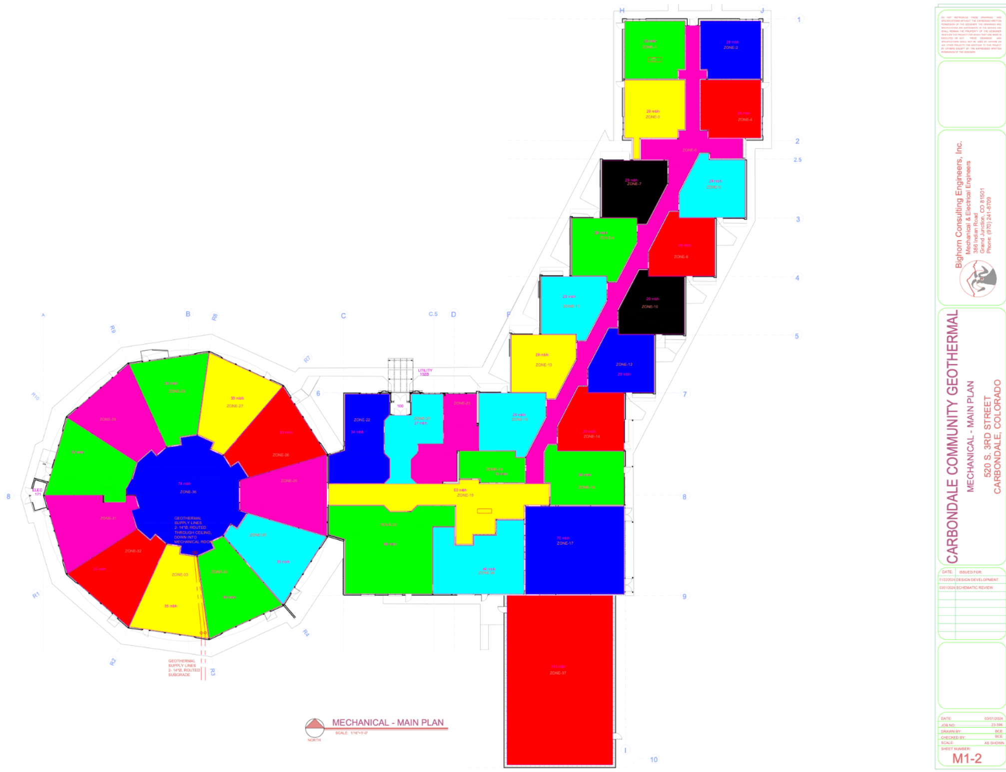


Figure 16: Thermal zones for each water-to-air heat pump

The retrofit design team developed three potential retrofit solutions for the Second Street Townhomes. We then held a design review meeting with the broader tech team and we decided to shift away from providing individual ground source heat pumps for each townhome because the retrofits would be very challenging and expensive to install while residents were living in their units. None of the townhomes, built in the 1970’s, are up to modern electrical code and they would require new meters, wiring, electrical panels, and potentially transformers that serve each bank of seven townhomes. The available water-to-air heat pumps also would have required extensive duct work and displacement to the residents while the work occurred.

At this design review meeting a fresh idea surfaced, which was to explore feeding the Second Street Townhomes with high temperature water from a central plant located in the basement of the Third Street Center. Such a high temperature loop (HTL) wouldn’t be able to provide cooling, but the tradeoff of having a straight forward and radically simplified retrofit path utilizing the housing units’ existing baseboard systems would be practical and achievable. The technical team had previously explored high-output temperature CO_2 heat pumps and thought that running a few of them in parallel would be a practical and scalable solution. The team also decided to implement an indirect water heater solution, where the domestic hot water (DHW) systems are also connected to the HTL to also decarbonize the domestic hot water systems of the Second Street Townhomes.

The basement of the Third Street Center is a large concrete room (formerly a bomb shelter from when it was a school). It currently serves as the mechanical room and overflow storage for tenants of the facility. The design team believes that it is an excellent location for the expanded mechanical room for the ATL pumps, internal TSC loop pumps, solar thermal pumps and heat exchangers, and to serve as the central plant for the high temperature water to water heat pumps serving the high temperature water loop that will circulate to the Second Street Townhomes for their heating and domestic hot water retrofits.

Bighorn Engineering delivered a set of Bid drawings for both the Mechanical & Electrical retrofits required for deployment. See Figure 17 below for the main Mechanical sheet followed by the Electrical sheet in Figure 18. The full bid set is available on GDR. These design specifications were highly detailed for the purposes of obtaining accurate contractor bids in preparation for the Deployment phase of the project.

Figure 17: Mechanical Retrofit Design main sheet

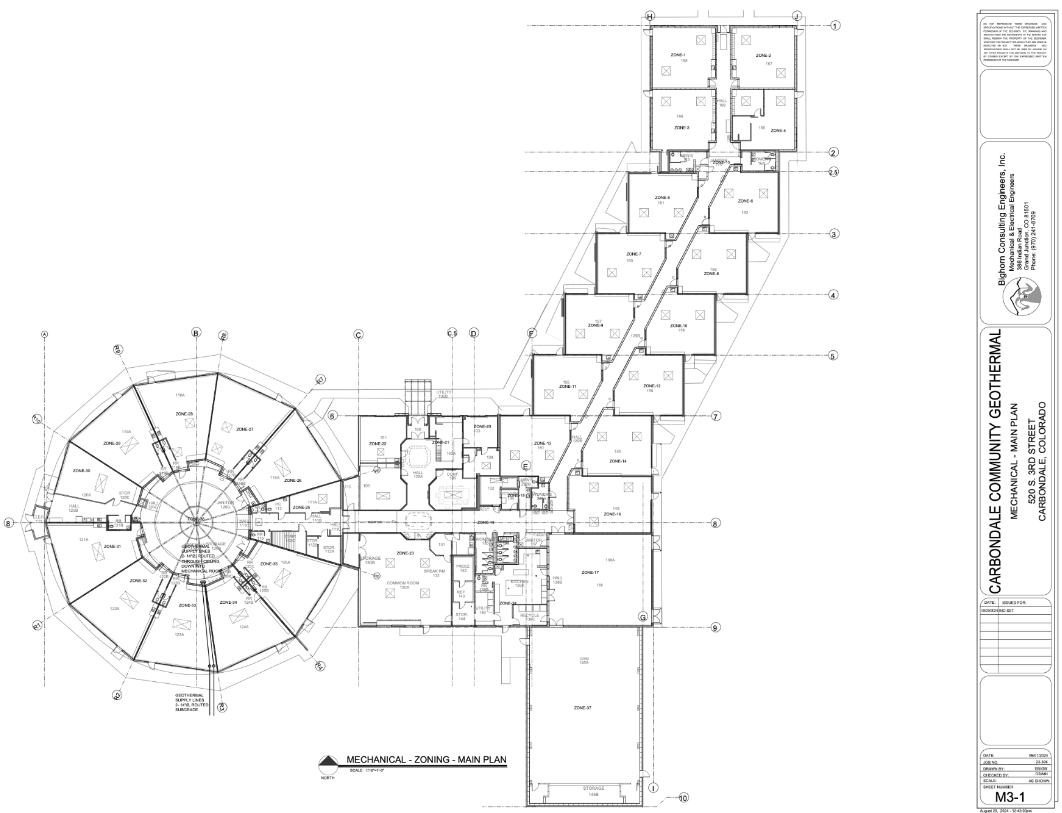
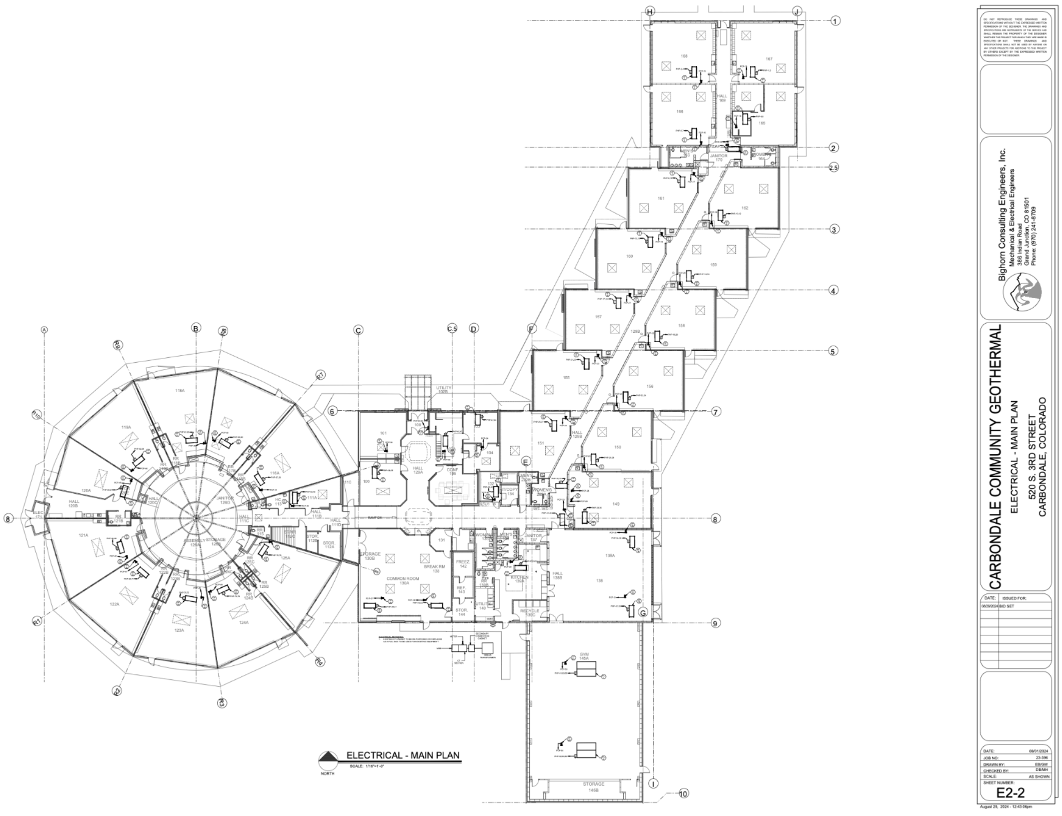


Figure 18: Electrical Retrofit Design main sheet



15. Auxiliary Thermal Resource Options

The design team explored two potential sources of heat energy to reduce the demand on the boilers and maximize the decarbonization potential of the system. These sources include harvesting wastewater heat from the Town of Carbondale’s sewer system and the expansion of the Third Street Center’s Solar thermal system with a tie-in to the ATL.

15.1. Wastewater energy exploration with the Town of Carbondale

The town of Carbondale’s utilities team provided wastewater system flows at two potential locations including the North side of Second Street and to the West of highway 133 and the Third Street Center. The estimated flow rates from the former are 6.6 gallons per minute while the latter are 13 gallons per minute. The recoverable power from the Second Street location was estimated to be ~1.75 kW and from the highway location to be ~3.5 kW with total potential annual energy recoveries of ~15 MWh and ~30 MWh, respectively. The larger site would contribute about 1% of the system's peak load requirement (*i.e.,* 400 kW) and 5% of the annual heating energy (*i.e.,* 574 MWh). The GreyEdge team felt that the investment to capture this waste energy would be too large to warrant additional consideration since both locations would require extensive design work, significant additional infrastructure, not to mention significant operational and maintenance costs.

15.2. Solar thermal energy exploration with Aspen Solar & NREL

The Third Street Center has an existing solar thermal system on its roof and the integrated design team explored various options of expanding and connecting this system into the ATL. Connecting a ground heat exchanger (Geo HX) with a solar-thermal heat exchanger (Solar HX) has been shown to work very well in cold climates. The design team worked with Aspen Solar, an experienced solar-thermal firm, and NREL's team to model a variety of scenarios with differing numbers of solar-thermal panels combined with differing numbers of bore holes in the Geo HX. The goal was to find an optimal solution that reduces the lifetime system cost and lifetime carbon emissions.

The method of the analysis was to run annual simulations for the two "default" geothermal-solar thermal models in Modelica. Then develop a matrix of scaled scenarios where the heat pump, pump, fan energy use, and heating load are scaled in Python to calculate the total ATL energy and supplemental boiler energy use. Finally, the lifetime emissions and energy use from 2025–2050 were calculated along with the social cost of carbon (SCC) to couple the emissions and cost metrics.

The key assumptions in the modeling are listed here (more details can be found in the final GTSTBoiler Study on the GDR repository):

- Emissions
  - Cambium highREcost, highNGprice, and midcase scenarios
- SCC
  - EPA 2025-2050 data with 2% discount[2]
- Energy Prices – from AEO 2023[3] forecast from 2025-2050
  - Natural gas price: based on EIA Henry Hub natural gas price
    - Averaged 1997-2023 ratios between CO and EIA Henry Hub data to get single multiplier for HH data. Calc CO prices = Forecasted HH data * multiplier
  - Electricity price: "Real Electricity Price" from EIA
    - Both electricity and natural gas can consider high and low oil and gas supply scenarios
  - Assume same system energy use from 2025-2050

- O&M costs are not considered

- CAPEX
  - Solar collector installation: $4000/panel
  - Collector cost: $1300-$1630
  - Solar collector connection to GHE: $20k
  - Borehole rate: $45/ft
  - GHE installation: $4k
- Cooling
  - Only included cooling loads for 3rd street center. Did not scale cooling loads.
- Boiler
  - Assume current Carbondale boilers (Two Lochinvar FTX600N boilers) are used
  - Staging based on min and max capacity; when two boilers are on, they run at the same capacity.
- Total forecasted lifetime (2025-2050) emissions
  - Used high and low decarbonization scenarios from Cambium (high = high NG cost, low = high RE cost)
- Total expected lifetime costs
  - Used EIA AEO 2023 Forecast
- Total expected lifetime costs with the social cost of carbon
  - Used EPA's social cost of carbon.

The results of this scenario optimization are shown in the next two figures. The Figure 19 illustrates the lifetime system cost (from 2025–2050) which includes the incremental capital investment, cost of energy to operated and the social cost of carbon for six sizes of the Geo HX based on the # of bore holes and nine sizes of the Solar HX. The second figure, Figure 20 illustrates the lifetime emissions (from 2025–205) for the same scenarios. The lowest lifetime system costs are when the Solar HX contains approximately 75 panels. There are a number of design factors and considerations that need to be considered to choose the optimum configuration, including the amount of cooling on the system and how much excess Solar HX energy can be stored in the Geo HX during the summer months. When aiming to minimize both lifetime system cost and emissions, the 75 solar panel and 60 or 75 bore hole scenarios are the most promising. The design team ultimately decided to design for 75 ST & 75 GT, as having the large bore field capacity should alleviate the need to stagnate the solar thermal system toward the end of summer in the event that the Geo HX cannot handle the trickle charge effect of accepting the excess energy.

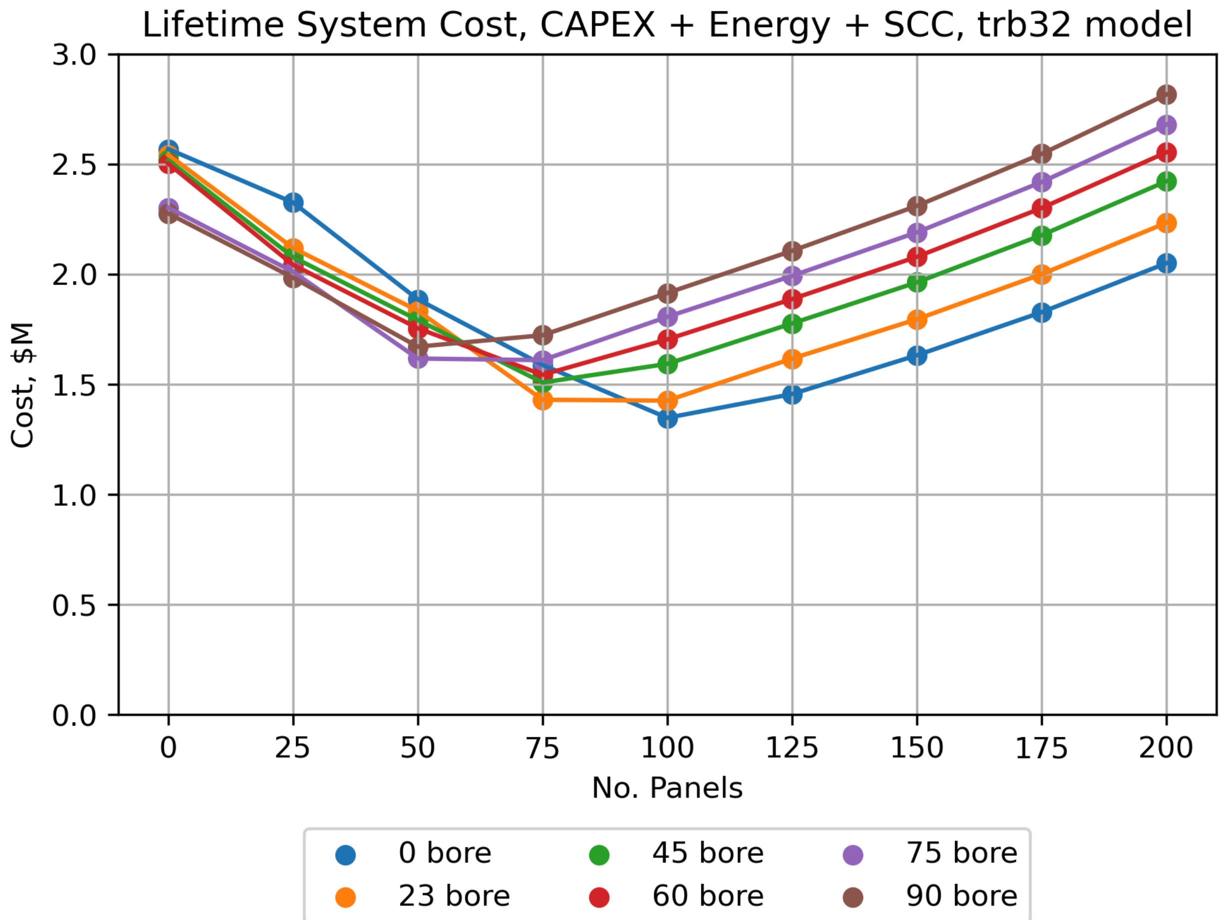
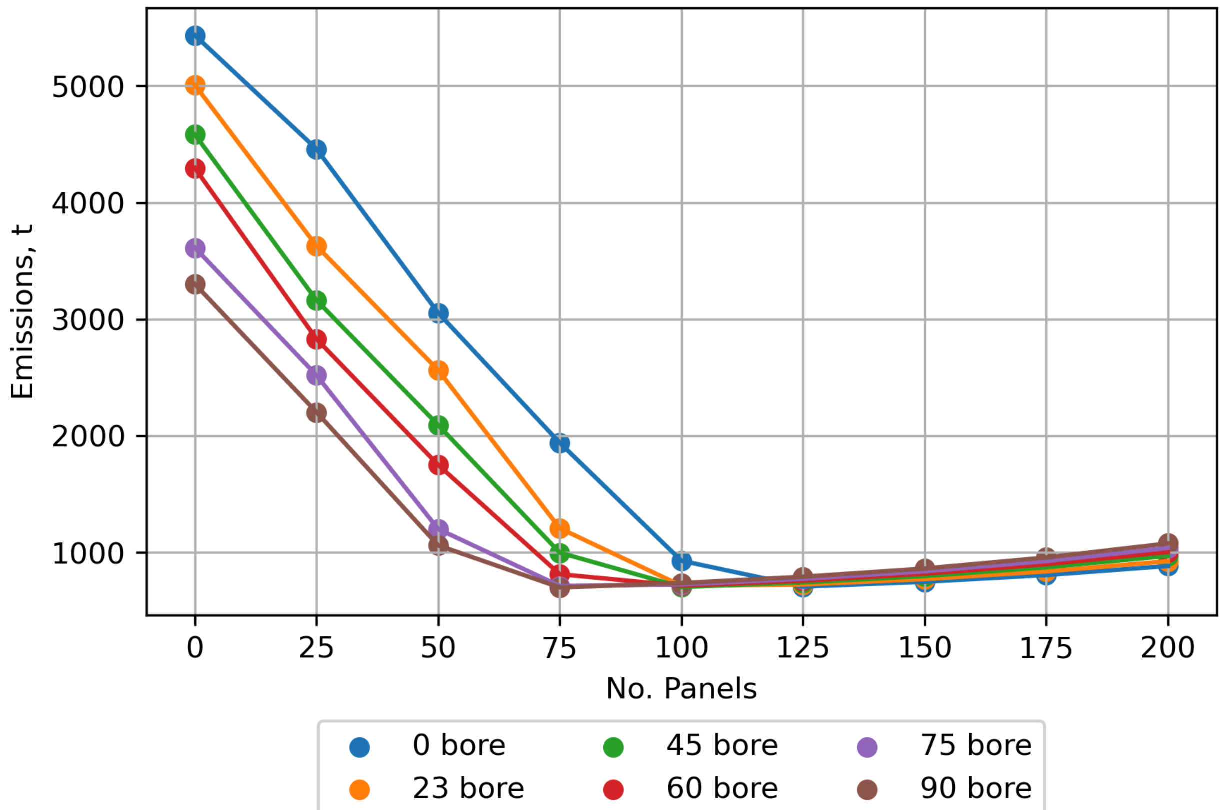


Figure 19: Lifetime system cost: CapEx + Energy + SCC

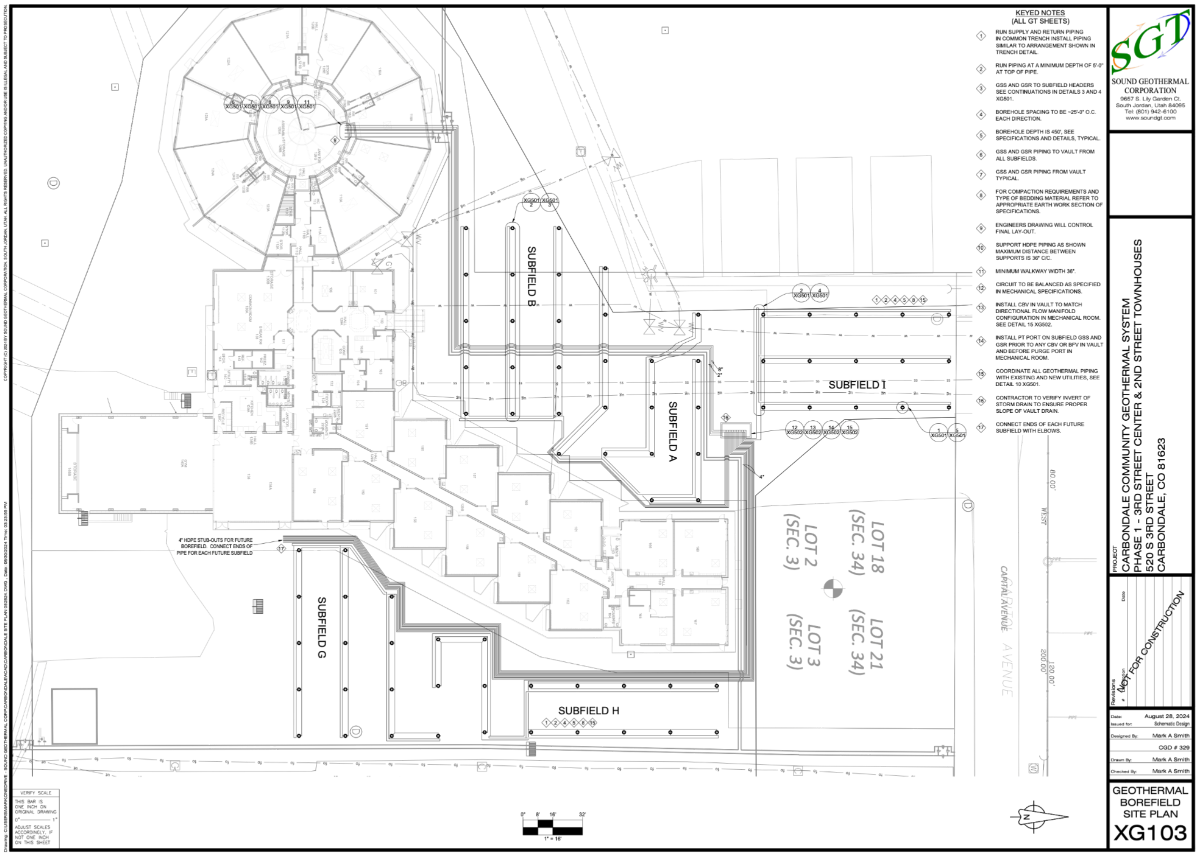
Figure 20: Lifetime CO_2 emissions (metric tons)



16. Bore Field and Ambient Temperature Loop Design Considerations

The integrated design and technical team met to review the optimization recommendations on the borefield, solar thermal contributions and overall ATL design. Representatives from the Third Street Center pointed out that the community gardens, Solar Oven and open space to the South of the Third Street Center weren't ideal locations for the bore field. Instead, they noted that underneath the existing parking lot to the North of the building would be a preferred location with fewer impacts and future constraints (*e.g.,* to the neighborhood to the South of the Third Street Center or to future expansion of the building). Thus, the GreyEdge Team reconfigured the bore field loops and ATL so they would be underneath the North and East parking lots. Figure 21 contains the final borefield and ambient temperature loop design based on the optimization recommendations from NREL of 75 bore holes plus 75 solar thermal panels. Note the solar thermal panels are planned to be located on the roof of the Third Street Center and are not included in this schematic.

Figure 21: Final borefield and ATL Design



17. Site Seismic and Geologic Considerations

After a local newspaper article on a local geologic feature called the Carbondale Collapse, the CLEER team was contacted by Don Marlin, a retired geophysicist, geologist, and geoscientist, who had experience in evaluating seismic and subsurface conditions. Mr. Marlin offered to look into some of the historical well data from the region along with other data including the geophysical maps to help the team understand the subsurface condition beyond those ascertained by the test bore hole and hydrogeologic report from Rich White of the GreyEdge Group. Mr. Marlin provided CLEER with a report on the subsurface and seismic interpretations of Carbondale and the surrounding Roaring Fork valley for the team to review. It is uploaded to GDR.

Mr. Marlin's summary recommendations in this report include the following:

- To present an interpretation based on additional subsurface / seismic since quads do not accurately depict this area as accurately as possible without these tools.
- Faulting that reaches the surface is a better basis for sinkholes than solely salt in town proper area.....but nearby evaporite outcrops and faulting creates further instability risk.

- Instability risk may be diminished by obtaining additional 2D seismic very close to the 3rd street Center area by providing additional subsurface control for drilling.
- Wellbore instability is likely to continue in the project area.

Because there is some risk of finding subsurface instabilities associated with drilling at this site the team will need to manage this risk in future implementation phases of the project. Obtaining additional seismic line data from a nearby location plus potential 2D or 3D acquisition efforts may be pursued in the deployment phase.

18. Workforce Development

Our approach to workforce development on this project is multifaceted where we are looking to increase awareness of geothermal systems as a key driver for meeting climate goals and to build a pipeline of education and workforce tracks. Our main tool for the former will be the development of a case study that describes the design approach along with the technical and economic results that can be used for a variety of awareness building and workforce development purposes. The education tracks start with skill building at the high-school and vocational levels, then add in certificate programs at the community college level, and ultimately get ground-source geothermal-system concepts embedded into undergraduate degree curricula. The workforce tracks include training and retraining curricula aimed at reaching a broad audience including HVAC installers, pipe fitters, engineers, architects, gas & oilfield services workers, entrepreneurs, and others who are already in the workforce. Ultimately, by fostering excitement and understanding around the science of geothermal systems and their unsurpassed efficiency, we aim to inspire people to rapidly scale and implement ambient temperature loop systems throughout rural areas and help the DOE meet its and our country’s climate and resiliency goals.

Our partners in this workforce development effort include New Energy Technologies, Colorado Mountain College, Garfield Clean Energy, GreyEdge Group, and National Renewable Energy Laboratory. New Energy Technologies is focused on high-school aged students. Colorado Mountain College has certificate programs, associate degree programs and bachelors of arts & science degree programs. Garfield Clean Energy is a regional partnership including all of the municipalities, the Roaring Fork Transportation Authority, Colorado Mountain College, Holy Cross Energy (a rural electric cooperative) and works with many regional contractors on energy efficiency programs. The GreyEdge Group is focused on practical certificate programs through the International Ground Source Heat Pump Association IGSHPA and Oklahoma State University, and the Heating Refrigeration Institute, while NREL is focused on higher level academic and professional publications.

New Energy Technologies has developed an education plus internship program focused on helping high school students develop their energy literacy skills and practical hands-on skills around building energy management. The program is well established throughout the Tacoma, WA public school district. For this effort, New Energy Technologies is discussing the rollout of their AEM Energy Champions program with a pilot at the Bridges High School of the Roaring

Fork School District—a member of the geothermal loop system. We have included an example slide deck here & at the end of this file. The example is of the AEM Bootcamp program that's being held this January at Tacoma public schools (note: it includes elements from EPA+DOE's Shutdown with EnergyStar). We will update this draft with more information on the progress of this effort within the Roaring Fork School District when we submit our full workforce development plan in August of 2024. Our team has experience with this kind of "grow our own" strategy where diverse students in our region become the future workforce, which will help our region scale up our just transition capacity even faster since many of these students already have housing in the region.

To equitably meet the project objectives the project team is also working with Colorado Mountain College (CMC), a Hispanic Serving Institution, to engage with their diverse students around this project and how clean energy careers can be exciting and rewarding. Our team is committed to creating pathways for students to gain exposure to STEM career opportunities and will also foster opportunities for apprentices and interns with our contractors. CLEER and CMC are planning to co-develop and evolve this draft workforce plan into a multiple pathway approach that includes their associates and bachelor's programs in natural sciences/sustainability and certificate programs in skilled trades/applied technology. CLEER will also work with CMC on our design case study to ensure that it is relevant and appropriate for CMC's diverse student population.

Garfield Clean Energy, managed by CLEER, helps the residents, businesses and local governments of Garfield County, Colorado, become more energy efficient and tap clean energy as a means to creating a stronger, more resilient economy. CLEER is preparing to launch its next-generation platform for tracking energy use and solar production in commercial and institutional buildings. CLEER's Advanced Energy Management service will replace Building Energy Navigator, the online tool used by 150 buildings and facilities in western Colorado. The platform is currently undergoing deployment and testing, and will be integrated into the workforce development plan as it is released to the Garfield Clean Energy Partners.

GreyEdge members and the Career Technology system in Oklahoma have developed an ongoing careers program for the trades in ground source systems. Multiple GreyEdge members are certified trainers of courses and hold certifications offered by the International Ground Source Heat Pump Association (IGSHPA). The project team will also include requirements for relevant certifications when we develop the project's design and installation specifications. The project team will look for opportunities to promote these trainings and certifications as viable career pathways for people both early in their careers and others who are mid or late in their careers. Some of the pertinent certifications are listed below from the IGSHPA website at https://igshpa.org/

- Accredited Installer (AI)
- Certified GeoExchange Designer (CGD)
- Certified Geothermal Inspector (CGI)

- Certified Residential Geothermal Designer (CRD)
- Train-the-Trainer Course (TTT)

National Renewable Energy Laboratory (NREL) researches, develops, and demonstrates technologies to advance the use of geothermal energy as a clean, renewable, domestic energy source for the United States. NREL publishes technical reports that are made publicly available, curates geothermal data and tools, and works with education institutes to provide lectures and seminars. In this project, NREL will coordinate with Colorado Mountain College to provide guest lectures on the basics and latest trend in geothermal technologies to inspire the future geothermal workforce. NREL will also collaborate with other organizations on the team to host public webinars on pertinent topics to benefit the geothermal workforce and the general public.

19. Technical, Economic, & Environmental Assessment

19.1. Technical Assessment of the Carbondale TEN

System Overview

The Carbondale Thermal Energy Network (TEN) is a community-scale geothermal system designed to provide heating and cooling to the Three-Two Zero Energy District (32ZED). This network uses a fifth-generation Geothermal District Heating and Cooling (GDHC) system, combining ambient temperature loops (ATL) and high temperature loops (HTL) to distribute thermal energy between various buildings. The key components of the system include a geothermal borefield, an ambient temperature loop, high-temperature loop, and water-source heat pumps installed in connected buildings.

Geothermal Borefield Design

The geothermal borefield forms the core of the TEN, where thermal energy is exchanged between the ground and the circulating water loops. The design features:

- **North and East Fields:** Boreholes are drilled to specific depths based on the thermal conductivity of the local subsurface material, ensuring optimal heat exchange during both heating and cooling seasons.
- **Manifolding:** Manifold systems are installed to connect boreholes, which allow efficient transfer of thermal energy between the subsurface and the ambient temperature loop.
- **Geotechnical Considerations:** Detailed geotechnical studies were conducted to assess the suitability of the site for borehole drilling, including geological, seismic, and hydrological evaluations. These studies confirm that the selected borefield locations possess high thermal conductivity and stable geological formations, minimizing the risk of system inefficiencies or structural issues over time.

Ambient Temperature Loop (ATL)

The ambient temperature loop is designed to distribute low-grade thermal energy across multiple buildings in the district. Its key design elements include:

- **Low-Temperature Heat Distribution:** The ATL operates at lower temperatures, typically between 50°F and 80°F, which reduces thermal losses during distribution and maximizes efficiency for low-energy buildings. This loop is primarily responsible for space heating and cooling.
- **Trenching and Pipe Installation:** Excavation and trenching have been planned to install underground piping connecting the borefield to buildings across the district. The materials selected for piping are highly resistant to corrosion and thermal degradation, ensuring longevity and minimal maintenance needs.
- **Pump Systems:** The ATL will utilize energy-efficient pumps installed in the Third Street Center (TSC) to circulate water through the loop. The pumps are equipped with variable-speed drives to adjust flow rates based on the real-time thermal demand of connected buildings, further improving system efficiency.
- Solar Thermal Support: An expanded solar thermal system will add heat energy into the ATL to augment the geothermal energy.
- Hybrid System with Boilers: Existing gas boilers will also be coupled with the ATL to provide heat energy during peak demand periods, thereby reducing the size of the borefield and the solar thermal system.

High-Temperature Loop (HTL)

The high-temperature loop complements the ATL by distributing higher-grade thermal energy to the older townhome buildings:

- **Higher Temperature Distribution:** The HTL is designed to operate at temperatures up to 170°F, providing heating to buildings that cannot be served by the ATL alone. This loop is vital for achieving full decarbonization of heating loads for buildings like the Second Street Townhomes.
- **Integration with Heat Pumps:** high temperature $CO2$ water-source heat pumps installed in the Third Street Center buildings will power the HTL. The system is also designed to accommodate future expansion and increased heat demands.

Thermal Energy Balancing

An important aspect of the system design is thermal energy balancing between heating and cooling seasons. The geothermal borefield is engineered to ensure that thermal energy extracted from the ground during the heating season is balanced by heat rejected back into the ground during the cooling season primarily from the solar thermal system since the cooling needs of the district are quite low.

- **Closed-Loop Design:** The system uses a closed-loop design to prevent groundwater contamination and ensure efficient heat exchange without loss of thermal fluid.
- **Annual Energy Balance:** Detailed simulations were performed to assess the annual energy balance. These simulations confirm that the ground temperature will remain stable over the long term, preventing thermal degradation of the borefield's efficiency over time.

Building Integration & Retrofit Design

The integration of the geothermal system with existing and newly retrofitted buildings is a critical component of the TEN:

- **Third Street Center Retrofit:** The TSC will be retrofitted with an internal heating and cooling loop connected to the ATL and HTL. Heat pumps installed in the building will utilize the thermal energy from the loops for space heating and cooling, replacing conventional fossil-fuel-based systems. Additionally, a solar thermal system will be installed to supplement the heating load and reduce peak demand on the geothermal system.
- **Second Street Townhomes Retrofit:** Similar retrofits will be performed in the Second Street Townhomes, with a focus on connecting these homes to the high-temperature loop. The heat pumps in these homes will be capable of efficiently extracting thermal energy from the HTL to meet both space heating and water heating demands.

19.2. Economic Assessment of the Carbondale TEN

The Carbondale Thermal Energy Network (TEN) project is designed to provide a community-scale geothermal heating and cooling system for the Three-Two Zero Energy District (32ZED). This economic assessment evaluates the cost-effectiveness of the project, its potential to reduce long-term energy expenses, and the broader economic impact on the community.

Capital Costs

The upfront capital costs for the Carbondale TEN project are significant, primarily due to borefield drilling, piping installation, retrofitting of existing buildings, and the deployment of both the Ambient Temperature Loop (ATL) and High Temperature Loop (HTL). Major cost categories include:

- **Borefield drilling and piping:** High initial capital investment is required for drilling geothermal wells and laying out the piping infrastructure.
- **Retrofits:** The Third Street Center and Second Street Townhomes will require substantial upgrades, including heat pump installations, electrical upgrades, and the implementation of internal geothermal loops.
- **ATL and HTL installations:** Excavation, trenching, and connection of both loops to the existing infrastructure will account for a significant portion of capital expenditure.

However, these costs are mitigated by several factors:

- **Federal and state tax credits:** Geothermal energy systems are eligible for federal tax incentives, such as the Investment Tax Credit (ITC), which can offset a substantial portion of the upfront capital costs.
- **Cost-share from local stakeholders:** Local partners are providing a 10% cost share, which reduces the financial burden on the project.

Operational Cost Savings

Once operational, the TEN is expected to provide significant long-term cost savings in terms of energy expenses for heating and cooling. Compared to conventional fossil fuel-based systems, the geothermal network offers the following advantages:

- **Lower operational costs:** Geothermal energy systems are highly efficient, with lower ongoing costs for electricity and maintenance. This results in significant reductions in monthly energy bills for connected buildings.
- **Stability of energy costs:** Geothermal systems are not subject to the price volatility associated with fossil fuels, ensuring predictable and stable heating and cooling costs over the lifetime of the system.

Energy Cost Comparison

A comparative analysis of energy costs between the geothermal system and traditional fossil fuel-based heating shows:

- **Fossil fuel-based heating systems** typically incur higher operating costs due to fuel price fluctuations and maintenance requirements.
- **Geothermal systems** have higher initial capital costs but lower long-term operational expenses. Over a 30-year lifecycle, the TEN is expected to achieve **significant energy cost savings**, particularly as fossil fuel prices rise in the future.

Additionally, the system's performance will reduce peak energy loads, which can result in lower electricity demand charges for users.

Lifecycle Cost Analysis

The lifecycle cost analysis indicates that while the initial capital investment is substantial, the long-term savings in operational costs will outweigh these initial expenditures. The overall payback period is projected to be **10–15 years**, depending on the level of energy demand from the connected buildings and the availability of federal incentives. After the payback period, the geothermal network will deliver substantial savings, as operational costs are minimal compared to traditional systems.

Economic Benefits to the Community

The Carbondale TEN project will generate broader economic benefits, including:

- **Job creation:** The project will provide local employment opportunities during both the installation and operational phases. This includes jobs in construction, drilling, retrofitting, and maintenance, with a focus on employing a diverse workforce, including underrepresented groups.
- **Reduced energy costs for residents and businesses:** By significantly lowering heating and cooling costs for connected buildings, the project will increase disposable income for residents and enhance the financial sustainability of local businesses.
- **Boost to local economy:** The savings generated from reduced energy costs will likely be reinvested into the local economy, creating a positive economic ripple effect throughout the community.

Cost Comparison: Individual Building Systems vs. District Heating

One of the key economic advantages of the TEN project is the **economy of scale** achieved through a district-wide heating and cooling system. In contrast to individual building heat pump systems (thermal islands), the district geothermal network offers:

- **Lower per-unit costs:** The shared infrastructure reduces the cost per building compared to installing individual systems for each building.
- **Centralized management and maintenance:** Centralizing the geothermal system reduces the complexity and cost of managing and maintaining multiple standalone systems.
- **Efficiency gains:** The district system allows for energy sharing between buildings, reducing overall energy consumption.

Environmental and Social Value

Beyond the direct economic benefits, the project offers additional value through environmental and social impacts:

- **Reduction in carbon emissions:** Transitioning away from fossil fuels will reduce greenhouse gas emissions, contributing to environmental sustainability.
- **Social equity:** The project aims to provide affordable energy to low- and moderate-income households in Carbondale, improving energy access and reducing energy poverty.

Economic Assessment Conclusion

The Carbondale Thermal Energy Network represents a financially viable project with significant long-term economic and environmental benefits. While the upfront capital costs are high, the availability of federal tax incentives, local cost-share contributions, and substantial operational cost savings make the project economically sound. The long-term benefits of reduced energy costs, job creation, and environmental sustainability far outweigh the initial investment, making this project a model for other communities considering district-scale geothermal energy systems.

19.3. Environmental Assessment of the Carbondale TEN

The Carbondale Thermal Energy Network (TEN) is a pioneering project aimed at providing sustainable heating and cooling through a district-wide geothermal energy system. The network will significantly reduce reliance on fossil fuels and minimize the environmental footprint of energy use in the Three-Two Zero Energy District (32ZED). This environmental assessment evaluates the project's impact on the local ecosystem, its contribution to reducing greenhouse gas emissions, and its alignment with environmental justice and sustainability goals.

Reduction of Greenhouse Gas Emissions

The primary environmental benefit of the TEN project is its contribution to reducing greenhouse gas (GHG) emissions. By transitioning away from fossil fuel-based heating and cooling systems to a geothermal district energy system, the project is expected to result in significant carbon emissions reductions:

- **Geothermal systems** are powered by renewable energy sources that emit virtually no GHGs during operation. This makes the Carbondale TEN a key contributor to Carbondale's efforts to achieve carbon neutrality by 2050.
- **Fossil fuel reduction:** Replacing traditional heating methods, such as natural gas boilers and electric heating systems, with this hybrid geothermal system will decrease the consumption of fossil fuels. This will directly reduce emissions of carbon dioxide (CO_2), methane (CH_4), and other harmful pollutants.

The TEN project is projected to lower GHG emissions by approximately **43% initially and up to 90%** as the grid is increasingly decarbonized, contributing to Carbondale’s, Colorado’s, and DOE’s broader climate goals.

Air Quality Improvement

By reducing the reliance on combustion-based heating systems, the TEN project will improve local air quality in Carbondale. Benefits include:

- **Reduction in particulate matter (PM):** Traditional heating systems, especially those relying on natural gas or propane, release particulate matter into the atmosphere, which can have adverse health effects. The shift to geothermal energy eliminates these emissions, leading to cleaner air.
- **Lower nitrogen oxide (NO_x) and sulfur dioxide (SO_2) emissions:** These pollutants, often emitted from combustion processes, contribute to smog, acid rain, and respiratory problems. By avoiding fuel combustion, the geothermal system will decrease NO_x and SO_2 emissions in the region.

Improved air quality will benefit public health, particularly for vulnerable populations such as children, the elderly, and those with pre-existing respiratory conditions.

Soil and Groundwater Protection

The Carbondale TEN project includes the drilling of geothermal wells and installation of an ambient temperature loop (ATL) and high-temperature loop (HTL). To minimize environmental impact during these operations:

- **Closed-loop system design:** The geothermal wells will use a closed-loop system that circulates a non-toxic heat transfer fluid, eliminating the risk of groundwater contamination. The fluid remains in the pipes, ensuring no contact with the surrounding environment.
- **Drilling and piping safeguards:** Best practices will be followed during drilling, including the use of advanced sealing techniques to prevent potential leaks or spills. Comprehensive geological inspections (as part of the borefield drilling phase) will ensure that the geothermal wells do not interfere with local groundwater supplies.
- **2D Seismic study:** Because there is some risk of finding subsurface instabilities associated with drilling at this site the team will need to manage this risk. Obtaining additional seismic line data from a nearby location plus a 2D acquisition effort will be pursued in the deployment phase.

The project will comply with all local and federal regulations governing drilling and groundwater protection, ensuring minimal disruption to underground water sources.

Land Use and Habitat Preservation

The Carbondale TEN project has been designed with careful consideration of local land use and ecosystem preservation:

- **Minimized land disturbance:** The geothermal borefield will be installed on pre-designated sites with minimal impact on existing land use. Areas chosen for drilling and piping are non-sensitive and do not disrupt critical habitats.
- **Site remediation:** Following construction, all borefield sites will be fully remediated, including re-grading, compaction, and revegetation of disturbed areas. This will ensure that the project has no lasting impact on the landscape.

Noise and Visual Impact

The Carbondale TEN project will have both noise and visual impact during construction but not during operation:

- **Noise mitigation during construction:** Drilling and excavation activities will produce some noise, but mitigation measures, including limiting working hours and using

noise-dampening equipment, will be implemented to minimize disturbance to nearby residents.
- **Minimal operational noise:** Once operational, geothermal systems produce very little noise compared to traditional HVAC units. This ensures that the system's long-term operation will not negatively impact the community.
- **Visual impact mitigation:** The geothermal borefield and piping infrastructure are underground, leaving no visible equipment at the surface. Additionally, the pump rooms for the HTL and ATL will be integrated into the basement of the Third Street Center ensuring minimal visual disruption to the community.

Alignment with Environmental Justice

The Carbondale TEN project prioritizes environmental justice by ensuring that its benefits extend to underserved and vulnerable populations:

- **Energy equity:** The geothermal network will provide low-cost, renewable heat energy to residents and businesses within the district, including low- and moderate-income households. By lowering energy costs and improving air quality, the project will help alleviate energy poverty and reduce health disparities.
- **Community involvement:** Local community members are actively engaged in the project planning and execution phases. This ensures that the project's benefits are distributed equitably and that all community voices are heard.

Climate Resilience

Geothermal systems offer increased climate resilience, particularly in the face of climate change. By reducing dependence on fossil fuels, the Carbondale TEN project will help the community adapt to future energy and climate challenges:

- **Stable energy supply:** Geothermal energy provides a reliable source of heating and cooling, unaffected by fluctuating fossil fuel prices or supply disruptions. This stability is particularly important as climate change increases the likelihood of extreme weather events and energy supply challenges.
- **Lower carbon footprint:** The TEN project will significantly lower the carbon footprint of the 32ZED, contributing to global efforts to mitigate the effects of climate change. The long-term environmental sustainability of the project aligns with broader state and national goals for reducing carbon emissions and promoting clean energy.

Environmental Assessment Conclusion

The Carbondale Thermal Energy Network represents a critical step toward environmental sustainability and energy resilience. By reducing greenhouse gas emissions, improving air quality, protecting groundwater, and prioritizing environmental justice, the project will have far-reaching benefits for the local community and the broader region. Its innovative design and implementation ensure that the environmental impact during construction is minimized, while the long-term environmental gains are substantial. As a model for future community-scale geothermal projects, the Carbondale TEN stands out as a transformative approach to achieving sustainability and climate resilience.

20. Operation and Maintenance Plan for the Carbondale TEN

The Carbondale Thermal Energy Network (TEN) is a community-scale geothermal heating and cooling system that requires regular maintenance, operational oversight, and capital repairs to ensure long-term efficiency and reliability. This O&M plan outlines the necessary activities, associated costs, and timelines over a 35-year period to maintain the system's performance, prevent failures, and manage operational expenses.

System Components Overview
The TEN system comprises the following components that require ongoing maintenance:

- Ambient Temperature Loop (ATL) – Provides moderate-temperature geothermal energy to the network.
- High Temperature Loop (HTL) – Supplies high-temperature geothermal energy, particularly for Second Street Townhomes.
- HTL Heat Pumps – Provide heating to the townhomes via the HTL.
- Solar Thermal Panels – Deliver additional thermal energy.
- Natural Gas Backup System – For peak heating demand beyond geothermal and solar capacity.
- Pumping Systems – Circulate water and heat through the loops.

Operating Costs

Assumptions:

- Electricity Cost: $0.0916 per kWh (Carbondale commercial rate).
- Natural Gas Cost: $1.42 per therm, with an annual natural gas usage of 0.13 BBtu for peak demand.
- Inflation Rate: 2.5% per year.
- Billing Costs: $5.00 per bill, managed by the Town of Carbondale.
- O&M Reserve Start: $125,000.

Pumping & Energy Costs

ATL Pumping Costs:

- ATL Pump Size: 18 kW.
- Duty Cycle: 10% (annualized).

- Annual Energy Use: 15,768 kWh/year = 18 kW × 24 hours/day × 365 days/year × 10%.
- Annual Pumping Cost: $1,444 = 15,768 kWh × $0.0916/kWh.

Solar Pumping Costs:

- Solar Pump Size: 0.5 kW.
- Duty Cycle: 22.3%. (annualized).
- Annual Energy Use: 979 kWh/year = 0.5 kW × 6 hours/day × 325 days/year.
- Annual Pumping Cost: $90 = 979 kWh × $0.0916/kWh.

HTL Pumping Costs:

- HTL Pump Size: 11 kW.
- Duty Cycle: 15% (annualized).
- Annual Energy Use: 14,454 kWh/year = 11 kW × 24 hours/day × 365 days/year × 15%.
- Annual Pumping Cost: $1,323 = 14,454 kWh × $0.0916/kWh.

CO_2 Heat Pump Costs:

- Heat Output: 0.296 GWh/year delivered to Second Street Townhomes.
- COP (Coefficient of Performance): 3.5.
- Electricity Consumption: 84,571 kWh/year = 0.296 GWh / COP.
- Annual Cost for CO_2 Heat Pumps: $7,748 = 84,571 kWh × $0.0916/kWh.

Natural Gas Backup Costs:

- Annual Gas Use: 0.13 BBtu/year.
- Annual Natural Gas Cost: $1,846 = 0.13 BBtu × $1.42 per therm.

Annual Maintenance Costs

- Routine System Maintenance:
  $2,500 per year for pump inspections, fluid chemistry checks, boiler monitoring, and control system calibration.
- Billing Costs:
  $5.00 per bill processed, based on the number of connected buildings.

Periodic Maintenance

- HTL Heat Pump Service:
  $7,500 every 7 years, covering refrigerant recharge and a full system check.
- Glycol Service:
  $4,440 every 15 years. This includes replacing the glycol used in the solar panels.
- Glycol Costs:
  $12 per gallon for 1.6 gallons of glycol per panel, with 75 panels in total.

Capital Repairs

Over the 35-year operational period, the following capital repairs and replacements will be required:

- ATL Circulator Pump Replacement:
  $12,000 in year 12, due to expected failure.
- Boiler Heat Exchanger & Burner Replacement:
  $30,000 in year 15 as part of planned repairs for the natural gas backup system.
- HTL Compressor & Recharge:
  $15,000 in year 17 to replace the compressor and recharge the HTL.
- HTL Heat Pump Refurbishment:
  $58,000 in year 20 to refurbish the heat pump system.
- Solar Panel Refurbishment:
  $12,600 in year 25 to replace or refurbish solar thermal panels.
- HTL Pump Motor Replacement:
  $6,000 in year 27, covering the motor replacement for the HTL.

Revenue Model

Revenue Sources:

- Townhomes Utilizing the Network:
  - Monthly rate per townhome: $55.
  - Revenue: Calculated based on the number of connected townhomes.
- Second Street Townhomes:
  - Monthly rate: $1,000 for connected units.
- Third Street Center (TSC):
  - Monthly rate: $1,000.

These revenues will cover the operating and maintenance costs, contributing to the system's financial sustainability.

O&M Reserve Fund

The O&M reserve fund will start with $125,000 to cover unexpected repairs or system malfunctions. This fund is expected to be used for both scheduled and emergency repairs, ensuring the system remains operational even in the event of unforeseen equipment failures.

Summary of Costs and Timeline

Annual Operating Costs:

- ATL Pumping: $1,444.
- Solar Pumping: $90.
- HTL Pumping: $1,323.

- HTL Heat Pump Operation: $7,748.
- Natural Gas Backup: $1,846.
- Annual Maintenance: $2,500.
- Total Annual Costs: $14,951.

Periodic Maintenance Costs:

- CO_2 Heat Pump Service: $7,500 every 7 years.
- Glycol Service: $4,440 every 15 years.

Capital Repairs:

- Year 12: ATL Circulator Pump Replacement ($12,000).
- Year 15: Boiler Heat Exchanger Replacement ($30,000).
- Year 17: HTL Compressor Replacement ($15,000).
- Year 20: HTL Heat Pump Refurbishment ($58,000).
- Year 25: Solar Panel Replacement ($12,600).
- Year 27: HTL Pump Motor Replacement ($6,000).

Operation and Maintenance Plan Summary

The Operation and Maintenance plan ensures the long-term sustainability and reliability of the Carbondale Thermal Energy Network (TEN). By adhering to the outlined routine and periodic maintenance schedules, along with timely capital repairs, the system will maintain optimal performance while minimizing operational disruptions. The inclusion of an O&M reserve further ensures that any unforeseen issues can be addressed promptly, protecting both the system's integrity and financial sustainability.

21. Conclusion

The Carbondale Thermal Energy Network (TEN) project represents a significant step toward achieving the community's carbon neutrality and renewable energy goals. By integrating geothermal heating and cooling systems within the Three-Two Zero Energy District (32ZED), this project highlights the potential for innovative energy solutions to transform community infrastructure, reduce greenhouse gas emissions, and enhance energy efficiency.

Throughout the project, several key findings were identified. The preliminary assessments confirmed that Carbondale's geological conditions are suitable for geothermal applications, with promising thermal properties that support efficient energy transfer. The building modeling and calibration efforts demonstrated that substantial energy savings and emissions reductions could be achieved through the implementation of a district ambient temperature loop and building retrofits. The system's design, featuring a hierarchical approach to energy distribution and utilization of advanced geothermal modeling tools, sets a strong precedent for similar projects.

Despite the positive outcomes, the project also faced several challenges, including regulatory uncertainty for thermal utilities, complex retrofitting of older buildings, and the need to manage subsurface risks. Addressing these challenges required innovative design adjustments, such as the potential incorporation of auxiliary thermal resources like solar thermal systems and high-temperature water loops, as well as extensive community engagement to foster awareness and support.

Thus, the Carbondale TEN project showcases a holistic approach to sustainable energy, integrating advanced geothermal technologies, community involvement, and targeted retrofits to create a replicable model for other towns and cities seeking to reduce their carbon footprint. As the project progresses to the deployment phase, the insights and lessons learned from this case study will be invaluable for future geothermal and zero-energy district initiatives, reinforcing the role of clean energy in building resilient and sustainable communities.

22. Outline: Expected Phase 2 Outcomes

IV. Deployment Phase

A. Project Planning

• Timeline and milestones

• Budget and funding sources

• Risk management plan

B. Procurement and Contracting

• Selection of contractors and suppliers

• Procurement of materials and equipment

• Contract negotiation and management

C. Construction and Installation

• Site preparation

• Installation of thermal energy network components

• Integration with existing systems

D. Commissioning and Testing

• System testing and quality assurance

• Performance verification

• Troubleshooting and adjustments

V. Challenges and Solutions

A. Design Challenges

• Technical limitations

• Integration with existing infrastructure

B. Development Challenges

• Budget constraints

• Supply chain issues

C. Solutions and Best Practices

• Innovative design approaches

• Efficient project management strategies

VI. Outcomes and Benefits

A. Energy Efficiency Improvements

• Reduction in energy consumption

• Cost savings for the non-profit development center and townhomes

B. Environmental Impact

• Reduction in carbon emissions

• Contribution to sustainability goals

C. Social and Economic Benefits

• Enhanced comfort and living standards

• Potential for community engagement and education

VII. Lessons Learned and Future Recommendations

A. Key Takeaways from the Project

• Success factors

• Areas for improvement

B. Recommendations for Future Projects

• Best practices for design and development

- Suggestions for policy and regulatory support

VIII. Conclusion

A. Summary of the Case Study

B. Final Thoughts on the Impact and Significance of the Project